Resilience of Urban Water Systems: An 'Infrastructure Ecology' approach to Sustainable and Resilient (SuRe) Planning and Design

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Resilience of Urban Water Systems: An 'Infrastructure Ecology' approach to Sustainable and Resilient (SuRe) Planning and Design

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SUMMARY

Increasing urbanization is a dominant global trend of the past few decades. For cities to become more sustainable, however, the infrastructure on which they rely must also become more efficient and resilient. Urban infrastructure systems are analogous to ecological systems because they are interconnected, complex and adaptive, are comprised of interconnected components, and exhibit characteristic scaling properties. Analyzing them together as a whole, as one would do for an ecological system, provides a better understanding about their dynamics and interactions, and enables system-level optimization. The adoption of this “infrastructure ecology” approach will result in urban development that costs less to build and maintain, is more sustainable (e.g. uses less materials and energy) and resilient, and enables a greater and more equitable creation of wealth and comfort. This research develops an 'infrastructural symbiosis' model to assess and quantify the synergistic non-apparent benefits that can be obtained through an infrastructure ecology approach.

Resilience, or the capacity of a system to absorb shocks and perform under perturbations, can serve as an appropriate indicator of functional sustainability for dynamic adaptive systems like Urban Water Systems. This research developed an index of resilience (R-Index) to quantify the “full-spectrum” resilience of urban water systems. It developed five separate indices, namely (i) Index of Water Scarcity (IWS), (ii) Relative Dependency Index (RDI), (iii) Water Quality Index (WQI), (iv) Index of Network Resilience (INR), and (v) Relative Criticality Index (RCI), to address the criticalities inherent to urban water systems and then combines them to develop the R-Index through a multi-criteria decision analysis method. The research further developed a theoretical construct to quantify the temporal aspect of resilience, i.e. how quickly the system can return back to its original performance level. This adaptive management

approach of R-Index as developed herein could be applied to other dynamic adaptive systems as well.

A novel approach used in this research to assess the complexity of urban water systems is graph theoretic network analysis. This research has shown that resilience can be increased by altering the topology of the system without any increased material and energy investment to augment system redundancy. Also, while there is a trade-off between residence time of water in the distribution system and increased resilience, there is no significant trade-off between resilience and flow efficiency for urban water distribution systems.

While there is a growing impetus of incorporating sustainability in decision making, frequently it comes at the cost of resilience. This is attributable to the fact that the decision-makers often lack a life-cycle perspective and a proven, consistent and robust approach to understand the trade-off between increased resilience and its impact on sustainability. This research developed an approach to identify the sustainable and resilient (SuRe) zone of urban infrastructure planning and design where both sustainability and resilience can be pursued together. This research shows that a SuRe zone of urban infrastructure development can be identified for different infrastructure components, hazards and topologies. Development of such an approach would enable stakeholders to make better informed decisions about urban infrastructure planning and development.

CHAPTER 1

INTRODUCTION

The global urban population is burgeoning and is projected to reach 7.0 billion by 2050, a 75% increase from the present tally[1]. With half of the world population being urban dwellers, and this distribution rising to 70% by 2050, urban centers are increasingly at the forefront of grand challenges for global sustainability. Though the current pace of urbanization is not unique in human history; but the enormity of urban growth - attributable to the massive demographic shifts in the developing countries - is unique, which poses major challenges for human health and the environment. However, while posing environmental problems, cities also offer solutions. As hubs of production, consumption, and waste generation, cities possess consummate potential to increase the efficiency of society as a whole in utilizing and consuming energy and natural resources.

Provision of infrastructure for this massive urban growth is certainly one of the most daunting challenges that this generation of engineers are faced with. However, the challenges faced by urban infrastructure in the developed and developing world are dissimilar in nature. While the developed world is coping with aging infrastructure, the developing world faces the challenge of keeping up with the brisk pace of urbanization and the rise in infrastructure demand.

Nonetheless, sustainability has grown from a preferred alternative to a necessary condition for urban growth and needs to be addressed at all levels to ensure the existence of a bountiful Earth a few generations down the line. Water infrastructure, in particular, is of paramount importance for the urban dwellers. It has been estimated that more than 2.2 million people die each year due to diseases associated with poor or non-existent potable water and sanitation facilities, mostly in the rapidly urbanizing developing countries[2]. On the other hand, up to 30% of fresh water supplies are lost due to leakage in developed countries due to aging infrastructure, and in some major cities, losses can run as high as 40 to 70%[2]. In addition to the problems associated with the failing or nonexistent infrastructure, there is a significant concern about how the impending climate change would affect the global water supply. Observed changes include increased events of drought and extreme rain events, which poses a unique challenge for the water utilities and the planners alike.

BACKGROUND OF RESEARCH

LIMITATIONS OF CURRENT PARADIGM

LACK OF SUSTAINABILITY DEFINITION

Despite the importance and criticality of water infrastructure in the sustenance of urban systems, no consensus has been reached about how to comprehensively quantify the sustainability of urban water systems. One of the predominant indicators of urban water sustainability is the proportion of people having access to safe water. The indicator developed as a core indicator by the UN is defined as "*Proportion of population with access to an improved drinking water source in a dwelling or located within a convenient distance from the user's dwelling. Improved drinking water sources include bottled water; rainwater; protected boreholes springs and wells; public stand-pipes and piped connections to houses*."[3]. However, this indicator of urban water sustainability is severely challenged in its scope as by definition it puts a household with "piped connections" at par with a household which has to devote time and energy – often a significant amount – to go over a "convenient distance" and get water for their daily need.

With increasing focus on sustainability, sustainability metrics have abounded in the recent years. However, in most cases these metrics are developed and defined to address the impact on environment by a process, a product or an entity. In terms of sustainability assessment, an increasingly popular method of sustainability assessment is the Life Cycle Analysis (LCA) method as defined in ISO 14040:2006, which is being implemented in all aspects of decision making process, including urban water, wastewater and stormwater systems. While performing an LCA and quantifying the impacts in terms of these metrics like ecological or carbon footprint excels in assessing the sustainability of a product or process in terms of its impact on the environment over its life-cycle; they are not particularly suited to assess the *functional sustainability* of a spatiotemporally dynamic system. Functional sustainability can be defined as *"maintenance of sustained functionality of a system amidst natural and anthropogenic stressors"*. Notwithstanding the importance of sustainable metrics in assessing the environmental impacts, in particular for dynamic systems, functional sustenance is of equal or more importance. Resilience or the *'ability to recover from or adjust easily to misfortune or change'* as defined by Merriam-Webster; has not been widely used as an important component of sustainability in the engineering paradigm. On the other hand, resilience has widely used as an indicator of functional sustainability for ecological systems [4,5]. Urban infrastructure systems function analogous to ecological systems in the sense that they both are complex, adaptive and spatiotemporally dynamic and hence resilience can be used an indicator of functional sustainability of urban infrastructure, rather than being a metric of sustainability in the narrower scale.

Compartmental Optimization of Urban Infrastructure

When considering how to reshape, redesign, or create urban areas to be more sustainable, it is imperative to include urban infrastructure systems (UIS) in the decision making process. UIS are durable features of the urban form and exhibit strong form of path dependence. Once built, UIS mediate the energy and resource flows into, within, and out of the urban areas for decades. To cater to the requirements of a 7 billion urban population by 2050, OECD has estimated that a 75% increase in urban infrastructure will be required with a projected global cost for infrastructure (re)development between $53 and $70 trillion, over the next twenty years[6]. Consequently, we need to get the design right to have the lowest possible life-cycle impact. It is therefore critical to study how best to design, build, and operate more sustainable UIS, especially given that more than 50% of the cities that we will have by 2050 have not yet been built. While existing UIS components are interconnected, each component of the UIS has generally been designed and optimized in a stove pipe manner, without full emphasis being given to the interactions between these components. This is not only wasteful but also leads to sub-optimal solutions.

There is one other major weakness in the current practice of UIS design and operation. Since the 1700s, with the advent of widespread *"engineered"* infrastructure, there has been an apparent conflict between engineered infrastructure and natural ecological systems. The engineered infrastructure components were built with the Romanesque big-pipe concept; the paradigm being that natural ecology needs to be scraped off and substituted by engineered alternatives, resulting in the *graying* of infrastructure. Notwithstanding the fact that this pattern of UIS design and operation has served humanity well over the last millennia, the manifestation of this paradigm has been pervasive. Most of the engineering decisions have been, and still are, being guided by this concept that *"engineering substitutes nature"* completely eluding the idea that *"engineering is indeed intended to complement/supplement nature"*. It is only in the past couple of decades, that there has been some acknowledgment of the fact that engineered (gray) and natural (green) infrastructure systems can be complementary[7]. Despite their criticality in attaining urban sustainability, UIS, especially the interdependence between these systems, have been undertheorized and empirically understudied[8].

CHAPTER 2

INFRASTRUCTURE ECOLOGY: CONCEPT AND APPLICATION

INFRASTRUCTURE ECOLOGY

UIS can be envisioned as complex dynamic adaptive systems comprised of six major components: 1) socio-economic flows resulting from infrastructure

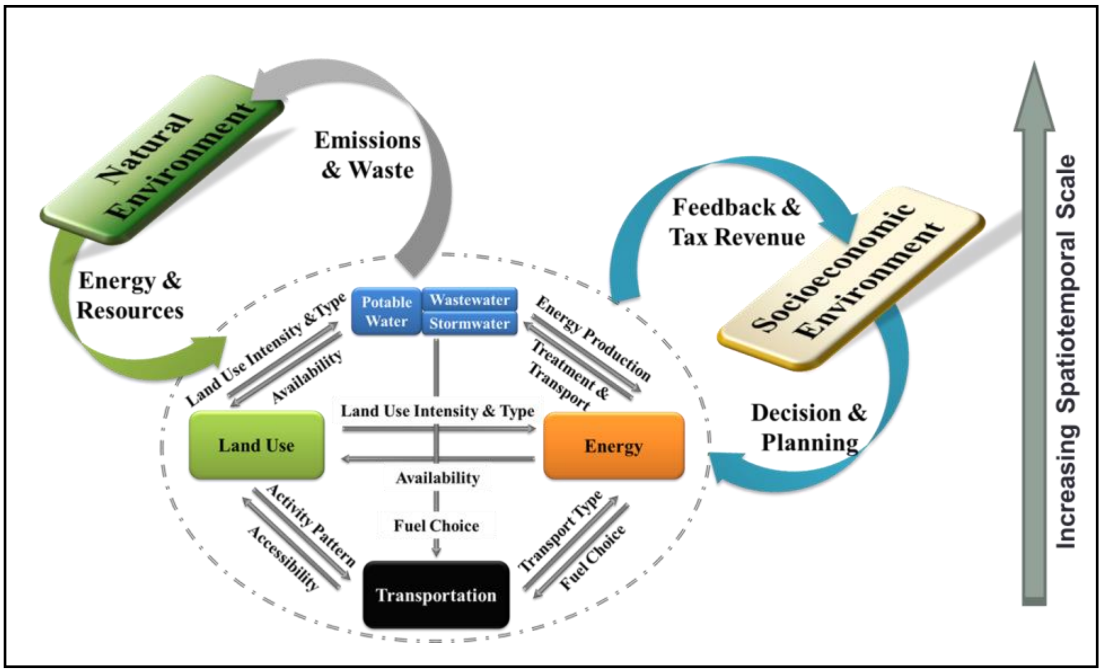


Figure 1: Interconnectedness within the Urban Infrastructure System (UIS) and the interrelation of UIS with Natural Environmental Systems and Socio-Economic Systems.

investment, 2) drinking water, storm water and wastewater infrastructure, 3) energy infrastructure, 4) transportation infrastructure, 5) land-use, and 6) the natural environment. These components are interconnected across spatiotemporal boundaries. While this component classification of UIS is predominantly *engineering* in its origin, it is actually the flows between these components that characterize the UIS and when analyzed holistically, function analogous to complex ecological systems. The analogy can be extended to the linkages with the earth ecosystems that provide the resources for these systems. In addition, the UIS are also interconnected with the socio-economic systems (Figure 1). The dense urban systems function on the basis of complex interactions and interdependence of the different aspects of the urban environment and infrastructure analogous to ecological systems. Ecology, as defined by the Merriam-Webster Dictionary *is 'the totality or pattern of relations between organisms and their environment'*. The concept of ecology can be extended to urban infrastructure when the urban infrastructure components are not analyzed individually but analyzed as an interlinked system. Urban infrastructure can be envisioned as an integrated network of four major infrastructure components, which are water, energy, transportation and land-use patterns, or the urban form as shown in Figure 1. A systems-level integrative approach reveals many options which might be more sustainable but not apparent when approached on an individual basis.

THE SYNERGISTIC EFFECTS OF INFRASTRUCTURAL SYMBIOSIS

Designing UIS with an infrastructure ecology approach could alter and reorganize the flows of energy and resources within the urban region, allowing one to consider the potential synergistic effects arising from infrastructural symbiosis. While individual technologies do exist to incorporate these effects, their application remains fragmented. A model of infrastructure symbiosis based UIS planning and design is shown in Figure 2, which outlines some of these synergistic effects. The effects and interrelations depicted here are not exhaustive, but provide a blueprint for holistic integrated infrastructure plans and designs for a few interactions. Taking the potable water, wastewater and stormwater sector as an example, the figure shows three additional alternatives of municipal water supply (both potable and non-potable water supply) compared to the traditional engineering concept of centralized water supply: (1) harvest of rainwater, (2) local reclamation of wastewater (both graywater and blackwater), and (3) retrieval of stormwater treated with LID techniques.

All of these options provide an urban community with a local source of supply and have a significantly lower energy footprint. The reduced energy consumption stems from two aspects: 1) the energy demand for distribution is significantly lower, and 2) the volume of water that needs to be processed for either drinking water or sewer treatment is reduced significantly. For example, a study of the City of Atlanta revealed that application of LID techniques to collect rainwater in all the residential areas would reduce the demand on the central supply system by over 30% or ~10 billion Gal per year[9]. This reduction in water demand yields an energy savings of 8.2 GWh and a 5,000 ton reduction in

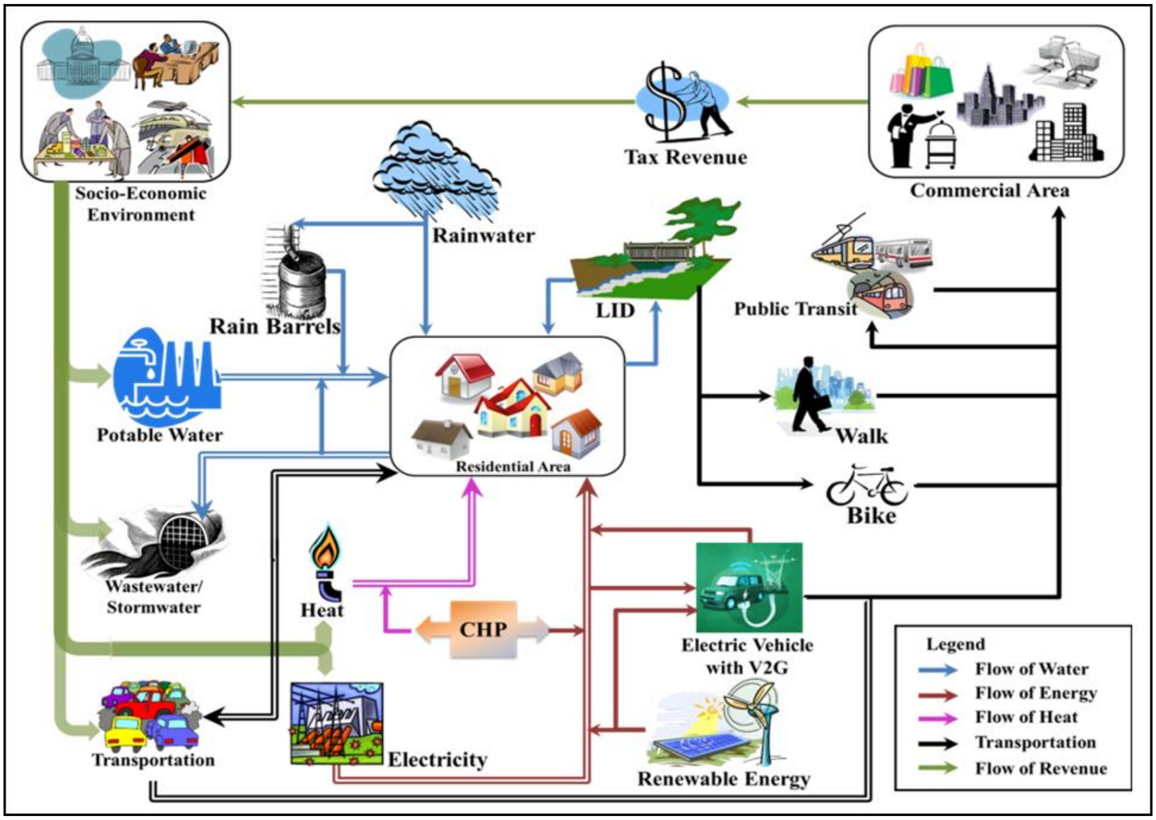


Figure 2: An example of infrastructural symbiosis for the proposed infrastructure ecology model.

Note: LID: Low Impact Development; CHP: Combined Heat and Power; V2G: Vehicle-to-Grid

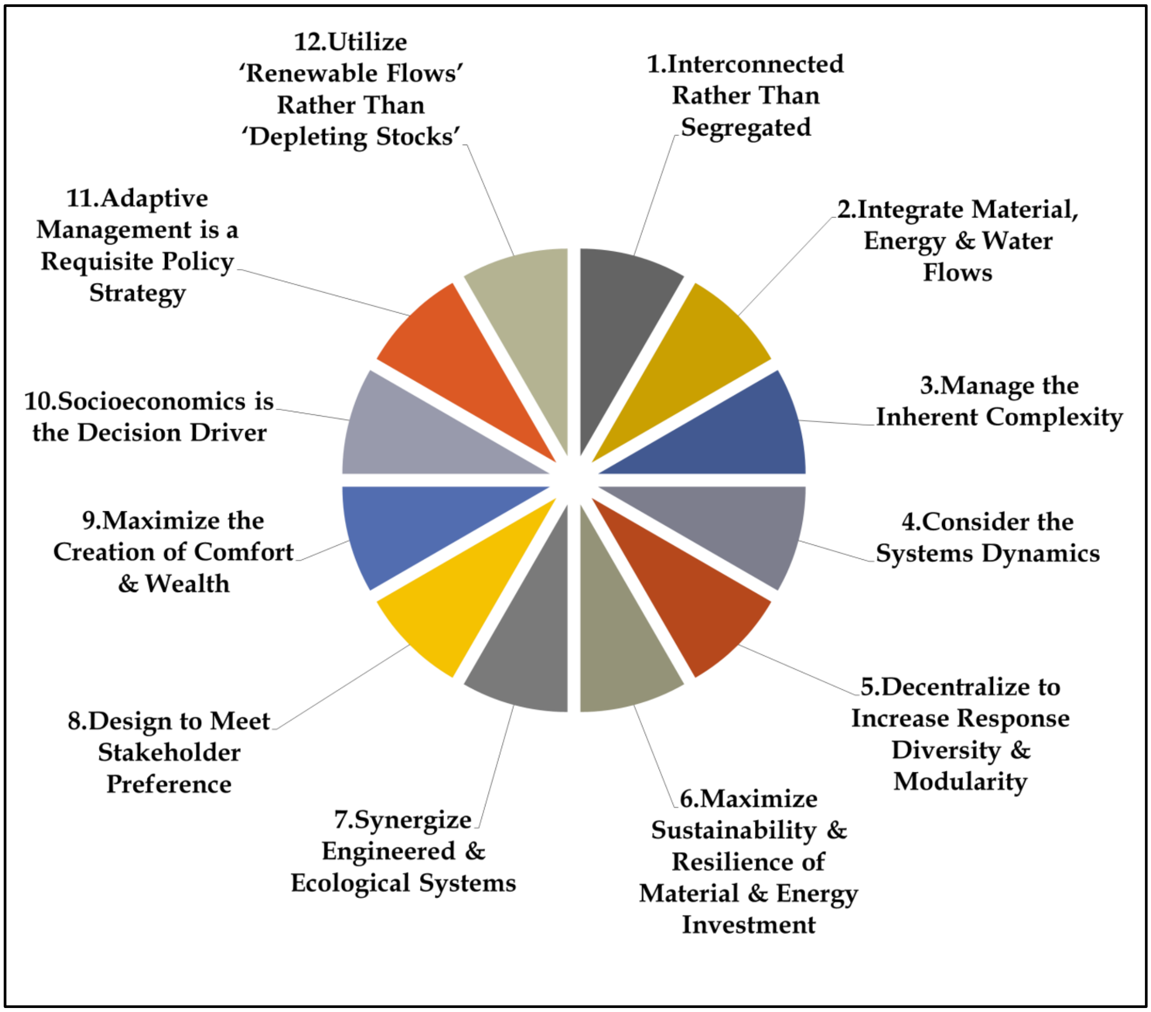
Double lines indicate conventional flows of water and energy;
Single lines indicate the reorganizations obtained through infrastructure ecology;
The depiction of water and energy flows is restricted to the residential area only for the sake of clarity. Water and energy flows to the commercial and other areas are present and share the same benefits of infrastructural symbiosis as with the residential area.

energy-related CO_2 emission on an annual basis – and this is in addition to the suite of other benefits discussed above. If the flows within the energy (heat and electricity) sector are similarly reorganized, certain phenomena emerge that could not be realized in a traditional engineering approach to UIS development.

For example, implementing air-cooled microturbines in a CHP framework nearly eliminates the *'water for energy'* footprint of electricity production, which makes the electrification of personal automobiles a far more attractive option. In addition, with the *increased accessibility of neighborhoods* that results from LID implementation, concerns about range obtained from a car battery is somewhat mitigated. This could increase the adoption of electric vehicles. Additionally, a large network of electric vehicles coupled with Vehicle-to-Grid (V2G) technology enables large-scale decentralized generation of renewable energy because renewable energy such as photovoltaics are subject to a great deal of variation. This variation, in turn requires utilities to increase the amount of spinning reserves. V2G allows energy to be exchanged both to and from the vehicle using the battery as an energy-storage device. The accumulated synergistic effects of this particular model of infrastructure ecology is significant: reduced water and energy consumption, lower dependence on centralized systems, larger share of renewables in the electricity mix, reduced vehicle-mile travel and an increase in tax revenue.

THE 12 PRINCIPLES OF INFRASTRUCTURE ECOLOGY

These 12 principles (see the following graphic) should be considered as parameters in a complex and interconnected system, similar to the 12 Principles of Green Engineering as proposed by Anastas and Zimmerman [10]. Since UIS is an integrated system, it is not be possible to optimize all of these principles



simultaneously. There are instances of synergy, as elucidated through the infrastructural symbiosis, where successful implementation of one principle augments one or more of the other principles. In other instances, where there is a lack of synergy, the goal should be to optimize the system solution.

I. Interconnected Rather Than Segregated

Urban infrastructure systems should be designed and optimized as an interconnected entity rather than designing and optimizing individual infrastructure components. This would allow the designers and planners to avoid the unintended consequences of compartmental optimization. The case of electrification of personal automobiles, as discussed above, can be considered as an example. With a microscopic focus on carbon reduction, inadvertently it exerts a surge in the water demand of the region.

II. Integrate Material, Energy and Water Flows

Material, energy and water flows should be integrated and optimized across the urban infrastructure system. Urban infrastructure components mediate the flows of material, energy and water within the urban system, reducing overall waste outflows. Failure to integrate these flows across the urban system would result in tradeoffs between the uses of the capitals, i.e. energy might be, and often is, sacrificed for gain in material flow efficiency. As an example, the case of air-cooled microturbine deployment in a CHP framework may be considered. The total WFE savings by and far outweighs the potential of water savings that can be achieved through the implementation of low-flow fixtures, drip irrigation for personal yards, or other water saving devices.

III. Manage the Inherent Complexity

Urban infrastructure systems are complex systems. Accounting for the complexity allows integrating some synergistic benefits that arise from emergent properties of complex systems. These benefits are non-apparent otherwise. As discussed with the concept of infrastructural symbiosis, the non-apparent synergistic benefits can only be assessed when system complexity is considered in design.

IV. Consider the Systems Dynamics

Urban infrastructure systems are dynamic-adaptive systems operating across multiple spatiotemporal scales. Systems dynamics should be considered to analyze and design urban infrastructure systems. The urban infrastructure system along with its socioeconomic and environmental counterparts is interconnected through feedback and query loops. Considering the systems dynamics into design would allow for the inclusion of effects that arise in these systems due to a positive/negative change in another system.

V. Decentralize to Increase Resilience, Response Diversity and Modularity

Decentralizing the urban infrastructure system increases the response diversity which increases the adaptive capacity and resilience of the system. Response diversity is defined as *the diversity of responses to environmental and demographic changes among infrastructure components that contribute to the same infrastructure function* (Adapted from Elmqvist, et. al [11]). In addition, decentralization (distribution of smaller components often acting in parallel to centralized systems) improves redundancy and allows gradual development of urban infrastructure to meet the increasing demand rather than speculative building of massive Greenfield infrastructure development.

VI. Maximize Sustainability and Resilience of Material and Energy Investment

Urban infrastructure systems should be designed to maximize its sustainability and resilience for any material and energy investment. Traditionally systems are designed to maximize the efficiency of investment in terms of benefit-cost analysis. To achieve the goal of sustainable urban development, the sustainability and resilience of capital investment (including assessment of natural capital) must be considered as often the solution that yields the maximum benefit-to-cost ratio might not be the most resilient or sustainable solution.

VII. Synergize Engineered and Ecological Systems

Engineered systems should be designed to integrate, complement, and where possible, regenerate the natural ecological systems. In addition to restoring and enhancing the ecological services, this would add to the resilience of the urban infrastructure system at a systems level by increasing its capacity to handle unexpected perturbations in the system. For example, as discussed above, implementation of LID technologies throughout the City of Atlanta could control the stormwater runoff from a 100 year storm event with relative ease and lower capital investment when compared to an engineering-only solution of building combined-sewer storage tunnels for runoff regulation.

VIII. Design to Meet Stakeholder Preference

Urban infrastructure systems should be designed to meet the stakeholder preference and policies should be designed to increase the adoption of sustainable and resilient infrastructure alternatives. Stakeholders play the most crucial role in adoption of any technology. In the instance where the design does not meet their preference, its adoption is likely to be underwhelming. Strategic policy decisions that encompass multiple infrastructure regimes should be able to encourage a greater adoption of sustainable and resilient alternatives for urban infrastructure. As an example, the development of the Atlantic Station development in the city of Atlanta, GA can be considered. Once a brownfield left behind by a steel plant which went out of business, it transformed itself into a thriving mixed-use neighborhood as it catered to the need of the local stakeholders.

IX. Maximize the Creation of Comfort, Well Being and Wealth

Urban infrastructure system design should strive for greater and more equitable creation of comfort and wealth for the residents while improving urban health. Sustainable urban development should focus on all of the three basic tenets of sustainability, environment, society and economics; not only on reduction of environmental impacts. In addition to reducing the environmental impact, sustainable urban development should also focus on maintaining economic prosperity, increasing social equity and improving environmental well-being.

X. Socioeconomics is the Decision Driver

Urban infrastructure system design is governed by socioeconomic decision making. It is not an absolute technical endeavor. Infrastructure planning and design should explicitly consider the role of socioeconomics and how it influences the when, where and how of infrastructure development. A prime example that can be considered is the effect of gentrification and how it alters the property tax base and other socioeconomic dimensions of a particular neighborhood and its implication on sustainable urban development/redevelopment.

XI. Adaptive Management is a Requisite Policy Strategy

Considering the uncertainties of the future and the associated risks, adaptive management should form the framework of policy decision making. Since attainment of 'absolute' sustainability is improbable, adaptive management strategies allows for gradual progress towards becoming more sustainable and allows recovering from any unfortunate setbacks that might occur in pursuit of that path.

XII. Utilize 'Renewable Flows' Rather Than 'Depleting Stocks'

Material, water and energy investment in new infrastructure development/rehabilitation of aging infrastructure systems should focus on utilizing renewable flows rather than depleting stocks. In an increasingly resource-constrained world, moving from nonrenewable resources to renewable ones is a requisite condition for sustainable development.

PRESENCE OF DYNAMIC-ADAPTIVE CYCLES

One of the key features of ecological systems is the presence of dynamic adaptive cycles which embodies the concept that systems are dynamic and are constantly passing through 'adaptive cycles' at various spatiotemporal scales [12]. The adaptive cycle, containing a fore-loop and a back-loop, is a conceptual model of the dynamics of the coupled anthropogenic and socio-ecological systems (Figure 3A).

This concept embraces the inevitability of a collapse of the system and subsequent reorganization to a shape of form which may or may not conform to the initial configuration of the system. These dynamic adaptive cycles are present in the urban infrastructure systems as well.

To ensure that all the criticalities of urban water systems are addressed, a monist approach would not suffice. While the reliability and the quality aspects can be addressed through the complex network approach, it really does not address the issue of water availability.

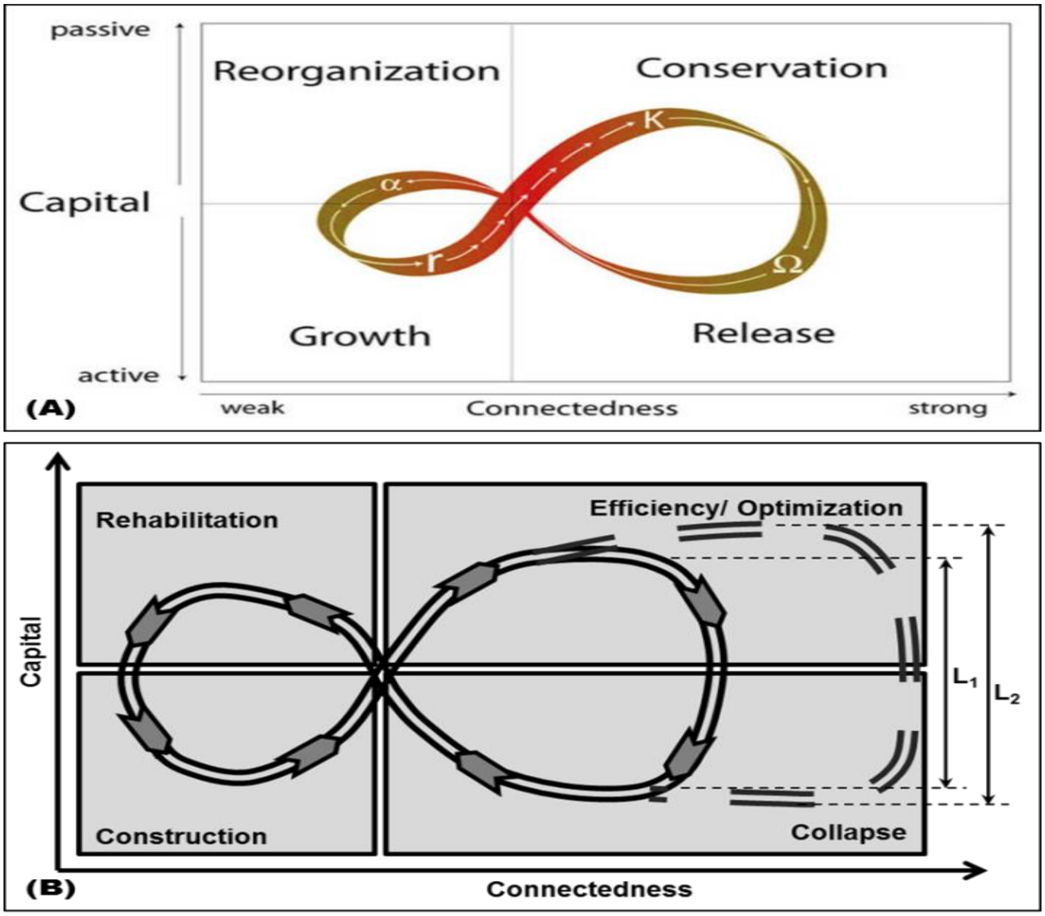


Figure 3: (A) The adaptive cycle approach for systems management.

(B) Modified adaptive cycle for urban infrastructure systems. L1 and L2 represent the losses in capital investment for the two different scenarios (fixed-line and dotted-line).

To address the water quantity issue, adaptive management technique provides the best alternative. Recreating Figure 3A (Figure 3B) in pertinence to the issues of urban infrastructure, the four phases can be visualized as: *construction, efficiency* or *optimization, collapse* and *rehabilitation*. The *construction* phase symbolizes the growth or building of infrastructure to cater to a certain targeted population with a particular life-span. In the *efficiency* or *optimization* phase, the infrastructure systems undergo improvements to increase the efficiency of their service, to optimize the output of the system, i.e. getting better at what they were doing. The *collapse* phase represents the period when the system loses its functionality, whether it is due to reaching the end-of-life or failing to cope up with the increasing demand, or due to natural and anthropogenic perturbations. Intuitively, the *rehabilitation* phase is the period when either the system is revamped or demolished and built from ground up. So, where does the problem lies in this model? The problem lies in the fact that the optimization phase often lacks innovation and exploration of alternatives and becomes too focused on optimizing the current practices. Recognizing the inevitability of collapse, as the optimization phase is prolonged, more and more capital (natural, human and man-made) gets stored in the same process and when it collapses the resultant loss is massive. Preemptive exploration of alternatives and use of innovative technologies would shorten this optimization loop and hence catastrophic loss can be avoided.

Taking the urban water system as an example, the optimization phase is being continued to be explored over the past few decades. The historic developments considered individual infrastructure components to be independent of one another and were built on the 'Romanesque' i.e. the 'big-pipe concept', causing irrecoverable damage to the natural environment. A paradigm shift is necessary in conceptualization of urban infrastructure to develop a sustainable infrastructure which is in harmony with natural and socio-economic environments. Centralized treatment systems coupled with lakes or rivers or groundwater wells as the source, has been the blueprint of almost any urban water system and indeed their efficiencies have increased over the years. This has also reduced the resilience of the systems significantly. If any of the treatment system in a city fails due to unforeseen circumstances, a major portion of the system is affected severely. This effect would be more pronounced in smaller cities where they might have only one central facility. Adaptive management strategies would advocate the exploration of alternative water sources for supply like rainwater harvesting and gray water reuse and some level of decentralization of the system shorten the optimization loop and going back to the construction phase which would allow partial avoidance of the collapse phase (Figure 3B).

PANARCHY

System thinking is not new in engineering, ecological or environmental science. A system can be defined as a group of interacting, interdependent parts linked together by exchanges of energy, matter, water and information, and is subject to a common plan or purpose. However, urban infrastructure at the systems level are not yet well understood, and research in this genre has remained largely unexplored. The degree of complexity increases significantly as the systems scale up. Walker et al introduced the concept of panarchy to describe the cross-scale effect of ecosystem[12]. Analogous to ecosystems, different mechanisms govern the interactions across different spatiotemporal scales within the urban regions, to confer resilience and adaptability to the system. All systems are composed of a hierarchy of linked dynamic adaptive cycles operating at different spatiotemporal scales (Figure 4). The structure and dynamics of the system at each scale is governed by a set of key processes, and in turn, it is this linked set of hierarchies that govern the behavior of the whole system. This hierarchical nesting of adaptive cycles and the cross-scale effects is termed as 'panarchy'.

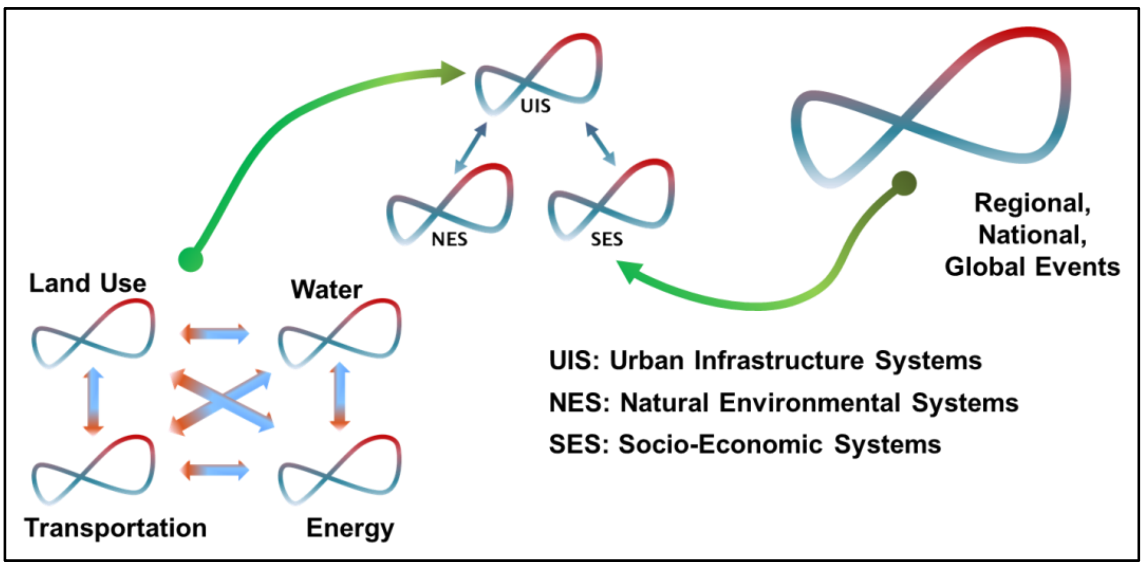


Figure 4: The hierarchical relation between Urban Infrastructure System, Natural Environmental System and Socioeconomic System operating at different spatiotemporal scales.

One of the observable examples of cross-scale dynamics in cities is the urban hydrology: The water table change in the drain of any backyard is caused by a precipitation event in the upstream of a watershed in a much broader spatial scale, in which the patterns of precipitation might be induced by extreme weather caused by the climate change. The small-scale land development would produce disturbance and impact to the hydrological regime at a broad-scale region, and may also create tremendous repercussion on an entire hydrological system of the watershed.

THE SPATIOTEMPORAL DIMENSION OF DECISION MAKING

With increasing levels of complexity within the systems arising from their interactions across different hierarchical spatiotemporal scales, traditional optimization approaches are not the preferred way to design, build and operate urban infrastructure systems. Traditional engineering optimization works well for local-short term systems (Figure 5). This research recommends the use of sustainable and resilience (SuRe) design for systems, which are local and short term in their scope, i.e. they operate on local-long term or global-short term scale.

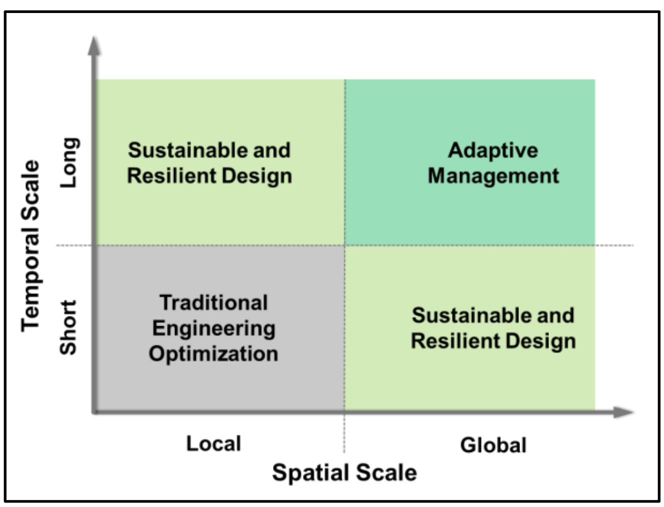


Figure 5: Urban Infrastructure System decision making space. Modified from Norton, 2005

If the scope of the system is both global and long-term, as in the case with natural environmental systems, adaptive management is the preferred alternative. This research makes a distinction the between SuRe approach and adaptive management. The SuRe approach of UIS design is still primarily a technological intervention to increase the capacity of the system to absorb shocks and reduce the response time after a perturbation. On the other hand, adaptive management approach explicitly includes policy intervention in the realm of UIS decision-making, with the goal to make UIS responsive and adaptable to changing scenarios through increased adoption of sustainable and resilient alternatives (both technological and behavioral) across the Urban system.

CHAPTER 3

THE INDEX OF RESILIENCE

URBAN WATER SYSTEMS: WATER RESOURCES AND INFRASTRUCTURE

Urban water systems can be envisaged to comprise of two major components: water resources and infrastructure. To address resilience or any other attribute of urban water system, the attribute needs to be addressed across both these categories, or in other words, an Integrated Urban Water System (IUWS) approach needs to be adopted[13]. IUWS integrates alternatives like use of stormwater and recycled wastewater as source substitution and enhancing water efficiency through demand management. Traditional engineering paradigm has categorically focused on pragmatic risk assessment and management techniques in the design and conceptualization of urban water systems and has failed to address the basic tenets of sustainability.

Earlier works in incorporating the criterion of resilience to water resource systems include those of Hashimoto et al. and Fiering[14,15]. Hashimoto et al.[14] introduced the criteria of reliability, resilience, and vulnerability to address issues related to temporal variability in water supply. Reliability was defined as the probability of the system benefits or performance being within an acceptable range, e.g., water demands met sufficiently; resilience as a measure of the recovery speed from a suboptimal performance level and vulnerability as a measure of the extent or severity of the unsatisfactory condition. However, this characterization of resilience is considerably constrained in its scope as it leaves out the reliability and vulnerability.

The recent studies on the resilience of urban water systems include both quantitative and qualitative studies. The study by Milman and Short[16], introduced a qualitative "Water Provision Resilience (WPR)", which encompasses six critical aspects of urban water systems: (1) supply, (2) finances, (3) infrastructure, (4) service provision, (5) water quality, and (6) governance. While this study excels in addressing the criticalities of the urban water systems, it does not attempt to quantify the resilience of the system. Later attempts in quantification of resilience of urban water systems predominantly focus on the reliability of supply based on the network structure of the distribution system and available pressure head in the network [17–21]. However, none of these studies attempted to address the future availability of water resources for supply and only the study by Zhang, et al.[19] focus on the water quality aspect. Though significant scientific research has been dedicated to resilience, no consensus has been reached on how to integrate the concept of resilience in urban water systems.

RESILIENCE: ENGINEERING AND ECOLOGICAL

Resilience or the 'ability to recover from or adjust easily to misfortune or change' as defined by Merriam-Webster, is one of the important metric of sustainability. The concept of resilience have been developed and implemented in the realms of engineering and ecology and consequentially there is significant difference between engineering resilience and ecological resilience. Engineering resilience is defined as the time required by a system to return to its original state of performance following a perturbation and carries an assumption of a single, global equilibrium. Ecological resilience, on the other hand, emphasizes instabilities which can "flip" the system into another regime of behavior, i.e., it acknowledges the existence of multiple equilibrium positions for the system, and can be defined as the magnitude of disturbance that can be absorbed before the system redefines its functional structure by changing the variables and processes that control the system behavior[22]. Infrastructure resilience has been of recent interest, as well as of concern, from the perspective of reducing the vulnerability when faced with natural or anthropogenic hazards. However, majority of these studies focused on the seismic resilience of critical infrastructure facilities [23–25]. A commonly used

The 4 R's of Resiliency

- ✓**Robustness:** *ability of the system to withstand a given level of stress and/or demand*
- ✓**Redundancy:** *measure of the inherent substitutability*
- ✓**Resourcefulness:** *measure of the capacity to mobilize resources in the event of disruption*
- ✓**Rapidity:** *measure of the capacity to contain losses or prevent further degradation in a timely manner*

measure of engineering resilience is the time required to revert the system back to its initial intended performance level. Resilience, according to this paradigm can be envisioned to be characterized by the 4 R's of resiliency, which are shown in the text box[25]. While the engineering concept of resilience focuses more the time required it fails to address two critical aspects of resilience: reliability and vulnerability of the system, arguably based on the *"semantic differences in the definitions of key hazard terms"*[24]. On the contrary, ecology adopts a more system-level holistic approach towards resilience, focusing more on the inherent capacity of the system to adapt and reorganize itself[4]. This study uses the Merriam-Webster definition of resilience to develop the framework for resilience of UWS as it incorporates aspects from both ecological and engineering concepts of resilience (Table 1).

Table 1: The concept of resilience used for this study and how it is related with general concepts of Engineering and Ecological Resilience

	Hazard Categories	**Resilience Capacities**
Engineering Resilience	***Misfortune:*** natural or anthropogenic hazards, aging infrastructure	***Recover from:*** post-disaster adaptive capacities
Ecological Resilience	***Change:*** variability in climate patterns, increasing population	***Adjust easily:*** pre-disaster inherent properties

INDEX OF WATER SCARCITY (IWS)

Water is primarily required to satisfy three types of demands: human (residential and industrial), agricultural and ecological (maintenance and sustenance of ecological systems). In the face of increasing concern over a changing climate pattern and increasing population, ensuring a sustained availability of water resources is one of the key issues that need to be addressed. Contentions over water rights for a particular watershed are prevalent both at the local, i.e. between different uses like residential, agricultural, cooling water for thermoelectric power generation; and the regional level, i.e. interstate disputes like the tri-state water dispute, which is an ongoing water use debate among the states of Georgia, Alabama, and Florida over the Apalachicola-Chattahoochee-Flint (ACF) River Basin and the Alabama-Coosa-Tallapoosa (ACT) River Basin. This research uses an index of water scarcity (IWS) to assess the stress on the available water resources for a particular region. Two separate indices have been developed to assess the relative and absolute water stress. While relative water scarcity index denotes the ratio of total water withdrawal to the total available renewable supply of water; absolute water scarcity index the ratio of total water consumption (including evaporative losses) as denoted in the following equations.

$$IWS\big|_{rel} = \frac{\left(w_{t,s} + w_{a,s} + w_{i,s} + w_{m,s}\right) + \left(w_{a,g} + w_{m,g}\right)}{S_W + G_W}$$

$$IWS\Big|_{abs} = \frac{1}{2}\left[\frac{\left\{\left(w_{i,s} + w_{a,s}\right) + \left(w_{t,s} - e_l\right) + \left(w_{m,s} - r_f\right)\right\}}{S_W} + \frac{\left(w_{a,g} + w_{m,g}\right)}{G_W}\right]$$

where, $w_{t,s}$ = surface water withdrawal for thermoelectric cooling,

$w_{a,s}$ = surface water withdrawal for agriculture,

$w_{i,s}$ = surface water withdrawal for industrial purposes,

$w_{m,s}$ = surface water withdrawal for municipal supply,

$w_{a,g}$ = groundwater withdrawal for agriculture,

$w_{m,g}$ = groundwater withdrawal for municipal supply,

r_f = return flow from residential supply;

e_l = evaporative loss from thermoelectric cooling;

S_w = total availability of renewable surface water;

G_w = total availability of renewable ground water

In the cases of agricultural and industrial water uses, the withdrawal and consumption are considered to be equal owing to their high evaporative loss and long return period. Furthermore, for groundwater the withdrawal is considered to be equivalent to the consumption since the withdrawn water is seldom returned back to the aquifer from which it was withdrawn. While IWS_{abs} provides the actual stress on the available water resources and is recommended to be used to assess the stress on water resources in a region,

IWS_{rel} should be used for regions, which are already water-stressed and do not have much latitude in increasing their water withdrawal capacity even though that water is not evaporated and is returned back to the watershed. It must be noted that G_W and S_W is also a function of the alternatives used to meet the total water demand within the urban system. Adoption of different alternatives alters the flows within the UWS. For example, in the traditional engineering paradigm the return flow from the municipal water supply is routed through a wastewater treatment facility for treatment and the effluent is released to the receiving surface water bodies. With exacerbating scarcity of available freshwater, increasingly municipalities are considering alternatives like wastewater reclamation. In this scenario, the wastewater (return flow) after being treated to a very high degree is injected back into the groundwater to retrieve later. While this would have little to no effect on IWS_{rel}, it would alter the relative stresses on S_W and G_W in IWS_{abs}. However, since the index developed herein is related to the total stress on all available water resources, the effect of alternative approaches would be minimal.

The *IWS* does not vary widely in a spatial scale, as in most cases an urban region is served by a single watershed. Temporally however, *IWS* exhibits significant variability based on the precipitation pattern, changing population, and changes in the behavioral pattern of the residents. It must be noted that the temporal variability is long-term in the scale of years to decades. However, with a changing climate pattern the variability in precipitation has been more pronounced over the past few years. S_W which can be expressed as,

$S_W = f\left(p, rw_h, e_v\right)$ where p denotes total precipitation, rw_h denotes harvested rainwater and e_v denotes evaporative loss; suffers significant variability in a shorter temporal scale. Hence, this study uses a moving average forecast for estimating the S_W availability. Moving average forecasting models has been touted to be one of the more successful models to analyze the time series of climatological variables[26]. On the other hand, G_W can be expressed as,

$S_W = f\left(i, w_{g,total}\right)$ *where* $i = f\left(p, l_c\right)$ where i denotes total infiltration and $w_{g,total}$ denotes total groundwater withdrawal. The total infiltration *(i)* in turn is a function of total precipitation *(p)* and land-cover characteristics *(l_c)*. l_c can be obtained through integrating the different types of land covers present in the watershed over their runoff co-efficient, assuming negligible loss due to evaporation during a storm event. Accordingly, this study uses a moving average forecast for estimating the G_W availability as well.

WATER QUALITY INDEX (WQI)

Ensuring that the quality of the water supplied to the consumers' faucet adheres to the stringent standard of potable water is of utmost importance in maintaining the functionality of the system. If the quality of the water being supplied is impaired for any reason, the entire system is rendered nonfunctional.

This study uses a holistic water quality index which incorporates seven different water quality parameters commonly recommended by EPA to ensure that the supplied water conforms to the potable water standard. These parameters are: Total Coliform Bacteria, Fluoride, Chlorine, Nitrate, Total Trihalomethanes (TTHM), Total Haloacetic Acid (HAA5) and pH. Their recommended values/ranges are shown in Table 2[27].

Table 2: Water Quality parameters and their MCL/MRDL and recommended ranges, where MCL and MRDL stands for Maximum Contaminant Level and Maximum Residual Disinfectant Level, respectively.

Parameter	MCL/MRDL
Total Coliform Bacteria	0.0
Fluoride (ppm)	4.0
Chlorine (ppm)	4.0
Nitrate as Nitrogen (ppm)	10.0
Total Trihalomethanes (TTHM) (ppb)	80.0
Total Haloacetic Acid (HAA5) (ppb)	60.0
	Range
pH	6.5 - 8.5

However, in terms of water quality neither of the parameters can be traded off with each other or with other indices. Hence, the WQI is expressed as:

$$WQI = \prod_{i=1}^{7} q_i$$

where, q_i denotes the value of the water quality parameters on a scale of 0 to 1

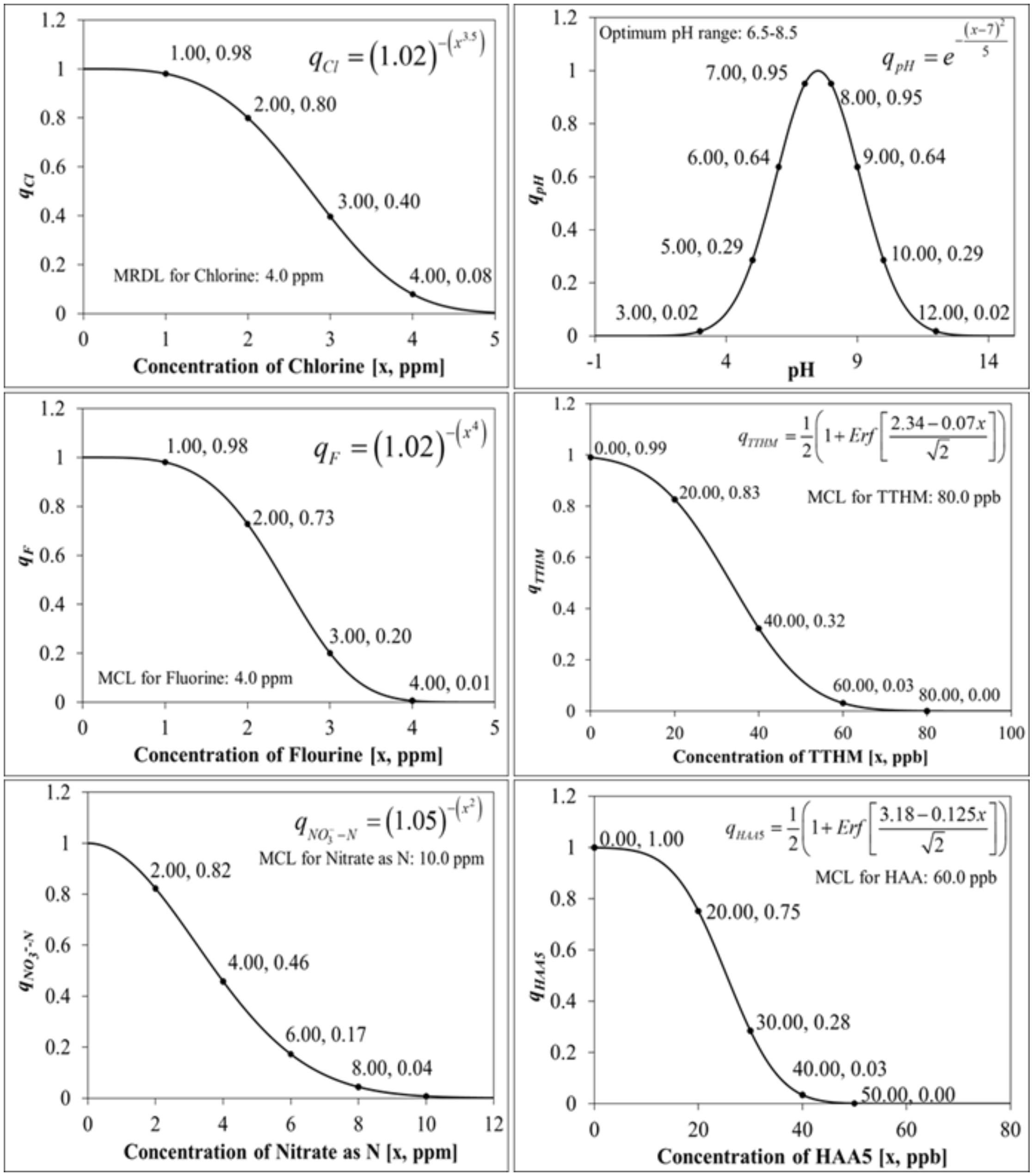


Figure 6: Postulated equations to estimate q_i for different water parameters. The graphs show representative values at different concentrations of the parameters.

depending on their concentration and MCL, MRDL or the recommended range. The values of q_i for these different water quality parameters can be estimated through the following set of postulated equations based on their concentrations, except for Total Coliform Bacteria (TC) count (Figure 6). With Total Coliform Bacteria, the value of q_{TC} is either 0 or 1 depending on whether any coliform bacteria are present or absent.

The WQI varies both spatially and temporally throughout the UWS. There is a continuous variability in WQI in the spatiotemporal scale. Typically the benchmark used to assess the water quality in an urban system, is the quality of water as it is leaving the treatment plant. However depending on the residence time of the water in the distribution network, which can be significant for large-scale water distribution systems, the quality of water that reaches the faucet of the consumer can be considerably worse than the quality leaving the treatment plant. Since the consumers are spatially distributed, the quality of water they receive is a dependent on how far they are located from the water treatment plant. With increasing residence time the concentrations of some constituents, like residual chlorine, for example decrease while that of others, like total trihalomethanes (THMs), and biological contaminants, may increase[28,29]. This study considers reactions of the constituents in both the bulk flow and at the pipe wall, using the model developed by Rossman et al[30].

INDEX OF NETWORK RESILIENCE (INR)

Water distribution systems being complex networks, a graph theoretical network analysis reveal several attributes related to the efficiency and resilience of the system. Six network metrics, ① graph diameter (d), ② characteristic path-length (l), ③ central-point dominance (c'_b), ④ critical ratio of defragmentation (f_c), ⑤ algebraic connectivity (λ_2), and ⑥ meshedness coefficient (r_m); were identified to quantify the efficiency, robustness and path redundancy of the network system. The aforementioned attributes, viz. efficiency, robustness and path redundancy, all are important attributes in terms of sustainability and resilience of a system. The metrics were then combined together to develop a composite index of network resilience (INR) to quantify the resilience of a distribution system based on its network topology. A Multi-Criteria Analysis (MCA) approach was employed to evaluate the alternative configurations which satisfy the hydraulic requirements of a network. An Analytic Hierarchy Process (AHP) was used to assign weights to the aforementioned attributes as it would allow tailoring the weights according to the requirements of the stakeholders and to cater to the particular geographic and demographic choices. Two different weighting scenarios were used for this purpose, one where all metrics were assigned weights to maximize efficiency of flow in the network and the other where weights were preferentially assigned to maximize the resilience of the network, to identify the possibility of potential trade-off between efficiency and resilience according to the layout of the water distribution network. The Anytown Network (AtN)[31] was used as case-study for this exercise. Using the hypothetical AtN as the base-case scenario, four alternate configurations was developed that satisfy the hydraulic demands (quantity of water, pressure) at each node. These four alternatives were then compared amongst each other and with the original configuration to assess the resilience and efficiency based on the network topology.

URBAN INFRASTRUCTURE SYSTEMS AND COMPLEX NETWORKS

Research in the genre of complex networks have increased in the recent years. Complex networks are usually characterized by a distributed system consisting of multiple interconnected components in a nontrivial configuration in which the function is reliant on the network structure or topology[32]. The interplay between network structure and their functionality is evident from the structure and functional attributes of two of the major classes of complex networks: scale-free and random. The scale-free networks are characterized by their non-uniform degree distribution which follows a power law, i.e. there are a few hubs with a lot of connections and majority of the nodes have a low degree of connectivity. Conversely, random networks have a vertex degree distribution, which adheres to a Poisson distribution, i.e. majority of the nodes have approximately the same degree of connectivity. This topological difference has a considerable impact on their resiliency. While scale-free networks are more resilient than random networks in case of accidental perturbations, they are more vulnerable than their counterpart in the event of targeted attack at the hubs. The ubiquity of complex networks as the core structural framework, i.e. the underlying skeletal framework of numerous technological and societal systems has garnered significant research interest to comprehend the dynamics of the network formation and growth in the recent past and has led into efforts to analyze the vulnerability and resilience of these networks against natural or anthropogenic perturbations. While there has been considerable research involving complex network in other infrastructure sectors[33–36] to estimate their performance through various surrogate measures of graph theory metrics, recent application of complex networks to analyze urban water systems is relatively sparse[37,38].

Earlier attempts in using graph-theory based network analysis for water distributions systems has mostly remained confined to reliability problems[39–46]. Jacobs and Goulter[41,42] showed that the most resilient topology of water distribution system would be a regular graph, i.e., each node have the same number of links associated with them. However, the inverse is not inevitably true due to the presence of bridges (links whose removal fragments the network) and articulation points (nodes whose removal along with the links associated to them fragments the graph)[47]. A widely used definition of reliability for urban water distribution systems come from the failure classes proposed by Ostfeld and Shamir[48]. They classified failures into two types: (1) failure of system components (mechanical failure); and (2) failure to meet the consumer demands (hydraulic failure) emphasizing a strong connection between these two types of failures. Consequential definitions for mechanical reliability and hydraulic reliability can be drawn from the above classification. A widely used graph-theory based method to assess the mechanical reliability of water distribution systems has been the minimum cut-set method[46]. However, minimum cut-set methods warrant excessive computational demand for large systems in particular[43]. The other significant effort in this genre was from Wagner et al.[49,50], who used graph theoretical approaches to estimate the reachability and connectivity[1] of a network system. According to Wagner et al's definition, reachability for a graph would always be greater than the connectivity and is a necessary condition for the system to be functional. This study uses graph theory metrics to provide a more comprehensive assessment all of the distribution system properties that were examined by the researchers mentioned above without excessive computational cost and burden.

Water distribution systems are spatially distributed systems where multiple components are connected by physical links. In a graphical representation of the water distribution networks, pipes and other connections represents the edges of the graph while demand and supply points along with the junctions, valves and pumps can be envisaged as the nodes in the graph. The

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[1] Wagner et al. [49,50] defined reachability of a specified demand node as the situation in which the node is connected with at least one source and defined connectivity as the situation in which every demand node is connected to at least one source. It should be noted that Wagner's definition of connectivity is not the same as the connectivity definition in graph theory, which is referred to later in this paper.

complexity of the resultant graph results from the complex interactions between the different components, uncertainty and nontrivial configuration of the system[37], which are not captured in the traditional engineering optimization methods. Traditionally urban water systems – distribution systems in particular – have been optimized with respect to the capital cost. Consequently, analytical and simulation techniques including linear programming[51], non-linear programming[52], integer goal programming[42] and Monte Carlo simulations[50] abounded, which have been employed depending on the scale and complexity of the problem. With the advancement in computation abilities, multi-criteria decision making (MCDM) analyses have been employed to incorporate other criterion like reliability of supply in the process of urban water-distribution system optimization through the use of genetic algorithms[18,53,54].

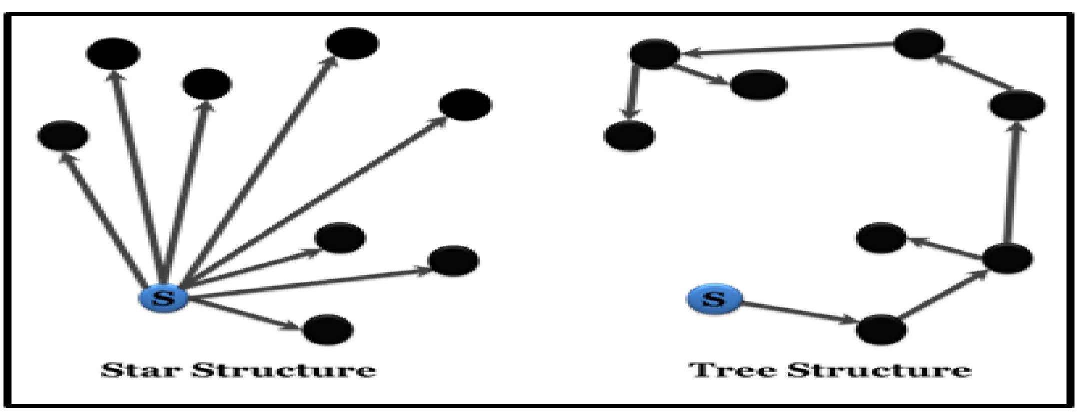


Figure 7: Schematic depicting star and tree structure network for identical spatial set of source and demand nodes.

To elucidate further, the following optimization paradox for water utilities can be considered. As discussed previously, utilities try to optimize the efficiency of water delivery while minimizing the cost. From the network perspective, while the former condition requires a star-shaped network the latter demands a tree-structure (Figure 7) and both scenarios would perform disastrously in the event of any disturbance. Interestingly, the two networks in discussion would perform radically different if the water quality at the consumer's faucet parameter is considered. The star network would perform best due to the low residence time of treated water in the distribution system and would be egalitarian to its consumers as all of them would receive the water having approximately the same residence time and quality. Conversely, in case of the tree structure, the consumers closest to the source would receive the best quality water and those further along the tree would receive the worst quality water. This is attributable to two reasons: 1) the residual chlorine would have longer time to react with background organic matter forming by–products, and 2) there would be increased probability of constituents (corrosion products and others) being leached from the pipe network. Complex network approaches, by virtue of their holistic topological analyses can overcome these challenges encountered in design and operation, while increasing the reliability of the system. Graph theory metrics in conjunction with the hydraulic parameters would provide a more robust framework for estimation of the performance and reliability of the system.

In general the structure of water distribution systems is correlated with the local topography and spatial distribution of the demand. In the node-link configuration of water distribution systems, the nodes can be distinctly grouped into source nodes, control and distribution nodes and demand nodes. On the other hand, the links are represented by the transmission and distribution pipes with different length, size and other physical attributes dependent on the material of the pipes. Essentially, the water distribution systems are directed graphs, i.e. the flow within the system is directional. However, the direction of flow in the distribution system alternates (except for those directly connected to the source or sinks) occasionally depending on operational flow and pressure requirements, rendering the consideration of water distribution systems as weighted digraphs exceedingly complex computationally. In addition, a comprehensive assessment for resilience of water distribution networks should also incorporate the nontopological specifications of the network, which include the size and material of the links and importance of the nodes. Though such an approach, would reveal a more realistic correlation between the topology of the network and the operational aspects related to the analysis of reliability of the network, it would require significant analysis of empirical pressure and flow data coupled with extensive simulation scenarios making the process too costly computationally[37]. Thus, this study treats the water distribution networks as undirected graphs and is based on the statistical properties of the network topology using graph theory to identify and recognize the structural patterns and building blocks of the networks. Water distribution systems are inherently vulnerable to both natural disasters, like earthquakes and anthropogenic hazards, like being potential targets for terrorist attacks[55]. While the vulnerability from natural hazards is dependent on both topological and non-topological (e.g. pipe material) attributes, vulnerability from anthropogenic perturbations is largely guided by the topological attributes of the system. While this approach might not be able to assess the vulnerabilities completely, it would provide a reasonable comprehension about the network structure and would be able to predict critical vulnerabilities associated with the topology of the network enabling the planners and designers to address the issues in the planning and design phase.

ANYTOWN NETWORK (ATN)

The Anytown network is a hypothetical network for a hypothetical Anytown, US. It has been used as the case-study in numerous studies about the optimization of using a suite of genetic algorithms[56], to determine the trade-off between reliability and total cost[53], entropy based design[57], to name a few. The town gets its water from a single source which is treated at a single centralized treatment plant. In addition, two overhead reservoirs are used in the system for storage purposes. The original configuration has 22 nodes, inclusive of the source and the reservoirs and 41 links or connections between the nodes. It was also assumed that all pipes have valves at each ends. Consequentially, all the alternate configurations have the same number of nodes, but they vary in the number of connection or links. While it is indeed possible to generate numerous alternatives, which meet the hydraulic demand at each nodes (without any restriction on the number of links), this study chose the four alternatives based upon two major criteria. First, the node: link ratio should be less than or equal to the original configuration and second, the metrics representing the network robustness should be greater than or equal to the original configuration. The range of alternatives chosen for this study might not be exhaustive but it still proves the basic premise of the study: a distribution system can be designed to be more resilient against natural and anthropogenic hazards based on the topology of the system. The alternate configurations would be termed AtN1, AtN2, AtN3 and AtN4 in this communication for the sake of brevity. The network representation of all the alternate designs along with the original configuration is represented in Figure 8.

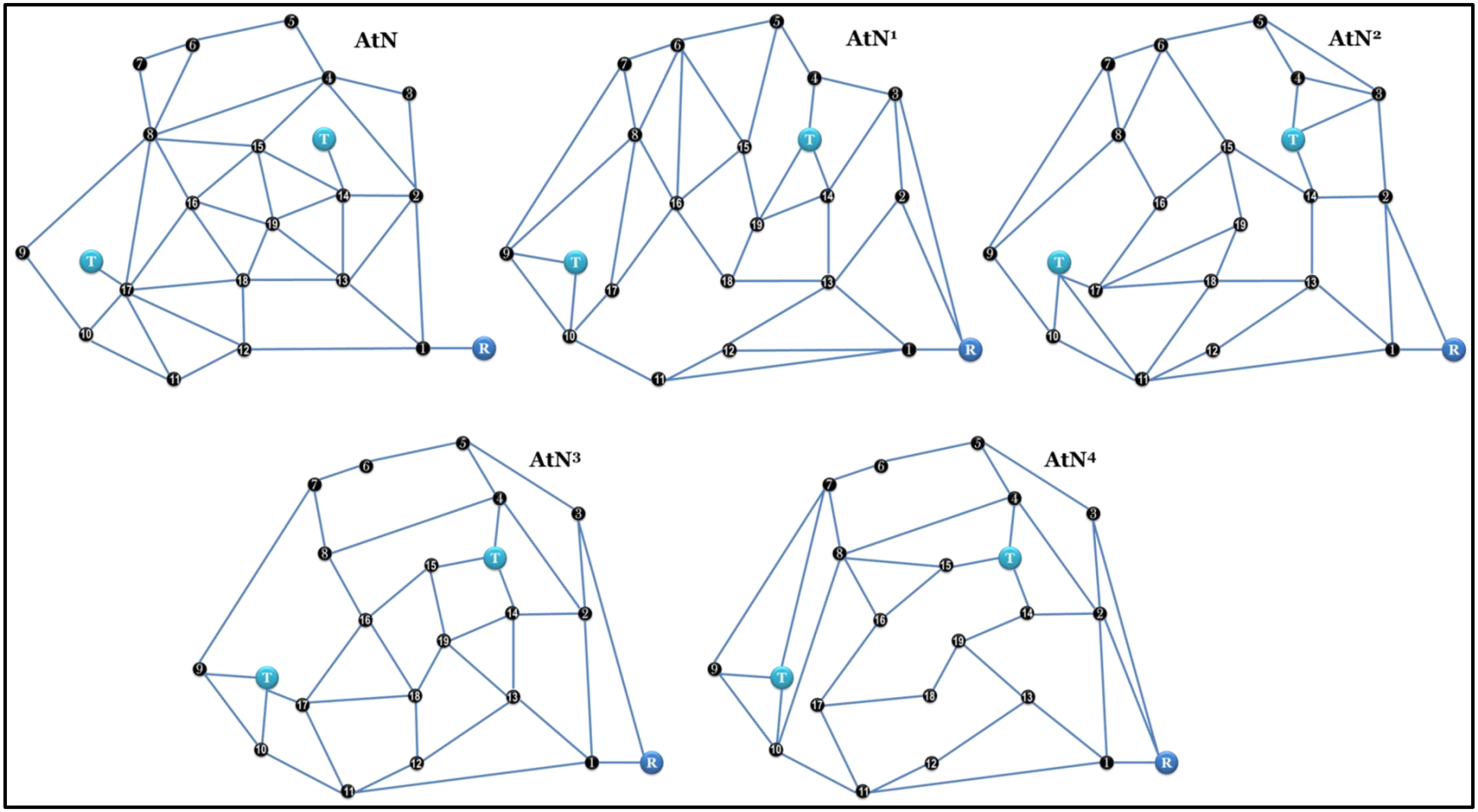


Figure 8: Network topology representation of the alternate configurations of the Anytown Network. Note: R represents reservoir and T represents elevated reservoirs. Drawing not to scale.

The framework for Index of Network Resilience (INR)

Network Metrics

This study incorporates six metrics of the network structure, ① graph diameter (d), ② characteristic path-length (l), ③ central-point dominance (c'_b), ④ critical ratio of defragmentation (f_c), ⑤ algebraic connectivity (λ_2), and ⑥ meshedness coefficient (r_m); to develop a composite INR. Among the numerous available network metrics which address efficiency of flow in the network, network robustness and network characteristics, the aforementioned were selected based on their capability to address issues in purview and their use in recent studies, which analyzed different urban infrastructure systems from the perspective of complex network analysis [33–37]. In addition, each of the chosen metrics addresses these issues through a unique approach. The first two attributes are related to the efficiency of the system, the third reflects the dominance of a particular node in maintaining the integrity of the network and the last three are surrogate measures of the robustness and path redundancy of the network to failure of one or more nodes or links.

In the graphical representation, any water distribution can be modeled as a mathematical planar graph $G = G(N, M)$, where N is the set of n nodes and M is the set of m edges in the graph. The efficiency of flow of water, or any other resource or information, per se, in a graph is characterized by the geodesic path length, i.e. the number of edges it has to traverse to reach from any node n_i to $n_{j,j\neq i}$ in an undirected connected path. The graph diameter (*d*) is a measure of the maximum graph eccentricity defined as the maximum value of the shortest geodesic paths, i.e. a graph's diameter is the largest number of vertices that need to be traversed in order to travel between any pair of vertices when paths which backtrack, detour, or loop are excluded from consideration. The graph diameter serves as a connectivity indicator of the network. A higher graph diameter indicates a sparsely connected graph which is not a desirable attribute for a centralized distribution system in particular, as in this case a portion of the distribution system can be cut-off from the central supply with relative ease.

The characteristic path length is the average of the shortest path-lengths in a graph, i.e. the average degree of separation between all nodes of the graph and can be obtained through the following expression:

$$l = \frac{1}{n(n-1)} \sum_{(i \neq j)} d_{ij} \qquad (1)$$

where, d_{ij} is the shortest geodesic path between nodes node n_i to $n_{j,j\neq i}$ in an undirected connected path and n is the number of nodes in the graph. Characteristic path length, though based on the geodesic distance, reasonably correlates with the Euclidean distance, i.e. the physical length, for real world infrastructure systems [58,59]. A shorter characteristic path length and a smaller graph diameter would be an indicator of higher flow efficiency within the network. Characteristic path length as a surrogate measure of efficiency has been demonstrated through previous research for different types of networks including transportation networks, neural networks and communication networks [60].

A critical measure of the structural organization of the network can be obtained through central-point dominance (c_b'), which indicates the dominance of the central point(s) of network in regulating flow within the network and the degree of concentration of the network around the central point(s). c_b' can be defined as the average difference in betweenness centrality between the most central point having the maximum value of betweenness and all others [61]. Betweenness is defined as a centrality measure of a vertex or edge within a graph. It is conceptualized as: vertices, which have a higher probability to occur on a randomly chosen shortest path between any two randomly chosen nodes, have a higher betweenness. c_b' can be determined through Equation 2.

$$c_b' = \frac{\sum_{i=1}^{n}\left[c_b\left(n_k^*\right) - c_b\left(n_i\right)\right]}{n-1} \qquad (2)$$

where, $c_b(n_k^*)$is the maximum relative betweenness centrality value around the central node k, $c_b(n_i)$is the relative betweenness centrality value for any node i in the network and n is the total number of nodes[2]. The betweenness centrality of node k can be obtained from Eqn. 3.

$$C_b(k) = \sum_{s \neq k \neq t \in V} \frac{\sigma_{st}(k)}{\sigma_{st}} \quad (3)$$

where, σ_{st} is the total number of shortest paths from node s to node t and $\sigma_{st}(k)$ is the number of those paths passing through node k. As implied from the summation indices, the betweenness centrality of a node scales with the number of pair of nodes. Thus this value may be normalized to a relative betweenness centrality value (c_b'), by dividing C_b with the number of pairs of nodes not including k, so that the lower and upper bound of the value of c_b' are 0 and 1. The value is 0 for graphs where all nodes have the same centrality value and is 1 for only star or wheel graphs. While graph diameter and characteristic path length are explicitly related to the efficiency of the network, central point dominance is related to both efficiency and robustness of the network configuration. A higher value of central point dominance would facilitate flow in the network rendering a more economical design. However, it would simultaneously make the network more vulnerable compromising its resilience. This is attributable to the fact that a high c_b' indicates high sensitivity of the network around the central point(s). It must be noted that c_b' is a measure of the

[2] The way the network structure was developed for this study, all the nodes in the network(s) are either supply or demand nodes and hence they all were accounted for in the set of nodes s.

dominance of hubs in a network; it does not consider supply nodes as the most critical ones. Water distribution systems are inherently vulnerable to attacks at or removal of supply nodes like reservoirs and tanks, which renders the entire system non-functional. So a higher value of c_b' indicates the presence of additional highly-connected hubs within the network, the removal of which would jeopardize the structural integrity of the entire system. With the increase in a number of critical nodes in the network (in addition to the supply nodes), the probability of one of these nodes being the target in case of a deliberate attack on the system increases. This would lead to deployment of greater resources in protecting these additional critical nodes.

The structural robustness of a network can be analyzed through studying the connectivity configurations and system performance of the network following a perturbation scenario of removal of one or more nodes and links due to random or targeted attacks. When complex networks are subject to random removal of nodes or links, i.e. a fraction f of the nodes are removed randomly, they can be analyzed as a case of infinite-dimensional percolation [62]. Percolation theory indicates the presence of a critical probability p_c, below which the network is composed of individual isolated clusters and above which there remains a giant cluster spanning the entire network. While the percolation theory is defined on a regular d-dimensional lattice, it meets random networks exactly in the infinite-dimensional limit $(d \rightarrow \infty)$ of percolation [63]. When f exceeds a certain threshold f_c i.e. the critical ratio of defragmentation, the network loses its large-scale connectivity and defragments. At an f value less than f_c, the network contains a connected cluster spanning the entire system, the size of which is proportional to the system size before perturbation. Exact solutions of f_c are available for two types of random networks – Cayley trees [64] and Erdös-Rényi random graph [65]. For any graph, f_c can be estimated from the following expression:

$$f_C = 1 - \frac{1}{\kappa_0 - 1} \quad (4)$$

where, $\kappa_0 = \langle k_0^2 \rangle / \langle k_0 \rangle$ is computed from the pre-perturbed graph, $\langle k_0 \rangle$ is the average node degree of the graph. This metric provides gainful comprehension about the robustness of the network in the event of catastrophic natural events like earthquakes. However, water and energy distribution networks are unique in their structural characteristics. The most critical nodes in these networks are not necessarily the hubs, i.e. the nodes with the maximum connection or the most central ones; rather they are the most influential ones, like the source nodes and the links directly connected to the source nodes. This individuality necessitates differentiation between the structural vulnerability of the network which can be estimated by fc and fault-tolerance of the network. The fault-tolerance of a network can be estimated by examining network properties that quantify the robustness and optimal connectivity of the network.

Algebraic connectivity, λ_2, as a measure of robustness and connectedness of networks was first introduced by Fielder (1973) and is defined as the second smallest eigenvalue of the normalized Laplacian matrix of a network. The Laplacian matrix of a graph G with n nodes is an n-square matrix $L = D - A$, where$D = diag(d_i)$, d_i being the degree of node i. $A = (a_{ij})$ is the adjacency matrix of the graph, where $a_{ij}=1$ if there is a link between nodes i and j, 0 otherwise. The smallest eigenvalue of a Laplacian matrix is zero having a multiplicity equal to the value of the network's connected components. For $n \geq 2$, λ_2 always have a positive value for any connected graph [66]. A larger value of λ_2 is an indicator of higher resistance offered by the network towards efforts to decouple the network. The larger the λ_2, the larger is the number of node- or link-disjoint paths in the network, i.e. the graph remains fully connected despite the removal of nodes or links. Two of the traditional concepts of network connectivity were the node connectivity $v(G)$ and the link connectivity $e(G)$[3]. λ_2 is upper bounded by $v(G)$ and $e(G)$ and proven to be a better indicator of network robustness and connectivity [66]. Algebraic connectivity as a measure of the robustness and the connectivity of complex networks has been used by many studies [68–71]. In particular, Jamakovic and Uhlig [69] ran probabilistic failure

[3] Link Connectivity is defined as the minimal number of links whose removal would result in losing connectivity of the network and Node Connectivity is defined as the minimal number of nodes whose removal together with adjacent links, would result in losing connectivity of network [67].

simulation on all major classes of complex networks, which corroborates that λ_2 can be used as a measure of the robustness of complex networks. Hence, λ_2 was adopted as measure of redundancy and connectivity for this study without repetition of the previous research efforts.

Another metric pertinent to the particular scenario of water distribution systems is the meshedness coefficient(r_m)[72]. For a distribution network with n nodes and m links, the number of independent cycles[4] in the network is represented by $f = m - n + 1$ for a single source system, by $f = m - n$ for a multi-source system and cannot exceed $3n - 6$ for any planar graph[37]. r_m is defined as the ratio of the actual number of cycles in the network to the maximum possible number of cycles in the network (bounded by $2\mathrm{n} - 5$).

$$r_m = \frac{f}{2n-5} \quad (5)$$

The meshedness coefficient quantifies the density of cycles in the network and is a measure of path redundancy in the network. A higher value of r_m indicates a higher probability of two nodes remaining connected despite a link failure. This six metrics have been evaluated for the original and four alternate configurations of the Anytown network developed for this study and are provided in Table 3.

[4] While cycles are defined as a path in the network in which no vertex except the first (which is also the last) appears more than once, loops are defined as edges that connect one vertex to itself.

Table 3: Network metrics of the original and four alternate configurations of the Anytown Network

Network Metrics	AtN	AtN[1]	AtN[2]	AtN[3]	AtN[4]
Graph Diameter (d)	5.00	5.00	5.00	5.00	5.00
Characteristic Path Length (l)	1.24	1.31	1.32	1.34	1.26
Central-point dominance (c'_b)	0.28	0.12	0.14	0.09	0.10
Critical ratio of defragmentation (f_C)	0.63	0.63	0.61	0.58	0.62
Algebraic Connectivity (λ_2)	0.56	0.44	0.51	0.57	0.67
Meshedness Coefficient (r_m)	0.51	0.51	0.49	0.41	0.44

Multi-Criteria Analysis (MCA)

While the network metrics discussed in the previous section are pertinent to the structural organization and resilience of the water distribution system, they are discrete and hence challenging to compare across different alternatives. A multi-criteria analysis (MCA) with preferential weight assignment through analytic Hierarchy Process (AHP) was used to combine these metrics into a single value score representing the INR for the alternate configurations. MCA provides an attractive approach to unify all these metrics in a composite index of network resilience to provide the decision makers with a single numerical value to appraise the alternatives. Two different cases have been considered in this study: ***Case-1:*** maximization of the resilience of the network based on its topology, and ***Case 2:*** maximization of the efficiency of flow in the network based on the structural topology. The relative importance of each metric can be represented by assigning weights to each metric. The goal of an MCA model is to assess a finite set of decision options or alternative scenarios based on a set of evaluation criteria. An MCA model can be represented by an evaluation matrix *(EM) X* containing n decision options and m evaluation criteria [73].

$$X = \begin{pmatrix} x_{1,1} & \cdots & x_{m,1} \\ \vdots & \ddots & \vdots \\ x_{1,n} & \cdots & x_{m,n} \end{pmatrix} \quad (6)$$

$x_{i,j}$ represents the raw performance score of alternative i with respect to criterion j. To warranty an outcome of the MCA evaluation there needs to be at least two alternatives and two decision criteria, i.e. $n \geq 2$ and ≥ 2 . The relative importance of each criterion is denoted by a one-dimensional weighing vector W which contains m weights, with w_j denoting the weight assigned to the j^{th} criterion.

$$W = w_1 \cdots w_n \quad (7)$$

The MCA evaluation aims to assign a utility score u, a single numerical measure of an alternative relative to the other alternatives; to each decision option by defining a utility function $u_i = f(X, W)$where $U = (u_1 \cdots u_n)$[74]. In cases where there is discrimination or strict dominance, i.e. one alternative outperforms all others against all criteria[75], certain criteria or decision options need to be excluded from the MCA model. As the graph diameter for all the alternate scenarios were identical it was excluded in further analysis. In order to develop a utility score *(u_i)* for each alternative, the raw performance scores *($x_{i,j}$)* for each criterion need to be transformed to a unit less value score *($v_{i,j}$)*. This study employed linear transformations, one of the most popular techniques employed in MCA[74]; to convert $x_{i,j}$ to $v_{i,j}$:

$$v_{i,j} = \frac{x_{i,j} - \min_{i=1}^{n}\left(x_{i,j}\right)}{\max_{i=1}^{n}\left(x_{i,j}\right) - \min_{i=1}^{n}\left(x_{i,j}\right)} \tag{8}$$

for a higher value of $x_{i,j}$ representing a better performance, and

$$v_{i,j} = \frac{\max_{i=1}^{n}\left(x_{i,j}\right) - x_{i,j}}{\max_{i=1}^{n}\left(x_{i,j}\right) - \min_{i=1}^{n}\left(x_{i,j}\right)} \tag{9}$$

for a lower value of $x_{i,j}$ representing a better performance, where $max_{i=1}^{j}\left(x_{i,j}\right)$ is the maximum value of $x_{i,j}$ for $i = 1 \cdots n$ and $min_{i=1}^{j}\left(x_{i,j}\right)$ is the minimum value of $x_{i,j}$ for $i = 1 \cdots n$. All the network metrics in consideration were converted to a unit less value score for the alternatives with the goal of maximizing the network resilience and efficiency. However, while a higher value of central-point dominance indicates higher efficiency a lower value indicates higher robustness and resilience. Hence, its value score was assigned accordingly to increase network resilience for the Resilience Scenario and to increase network efficiency in the Efficiency Scenario. The value matrix for both the scenarios is represented in a tabular form in Table 4.

Table 4: Value matrix for the two scenarios considered for this study. ↑ indicates that a higher value of the metric is preferred for that particular scenario while ↓ indicates that a lower value of the metric is preferred for that scenario.

Metric	Resilience Scenario						Efficiency Scenario					
		AtN	*AtN¹*	*AtN²*	*AtN³*	*AtN⁴*		*AtN*	*AtN¹*	*AtN²*	*AtN³*	*AtN⁴*
l	↓	1.00	0.53	0.47	0.33	0.87	↓	1.00	0.53	0.47	0.33	0.87
c'_b	↓	0.00	0.86	0.77	1.00	0.95	↑	1.00	0.14	0.23	0.00	0.05
f_C	↑	1.00	1.00	0.78	0.44	0.90	↑	1.00	1.00	0.78	0.44	0.90
λ_2	↑	0.63	0.23	0.46	0.66	1.00	↑	0.63	0.23	0.46	0.66	1.00
r_m	↑	1.00	1.00	0.88	0.38	0.57	↑	1.00	1.00	0.88	0.38	0.57

AHP was used to assign weights to the network metrics. AHP essentially arranges the criteria in a hierarchical manner to satiate the goal or objective of the MCA[76]. In AHP the criteria are compared pair wise based on a semantic scale of 1-9, which is defined to indicate how many times more important or dominant one element is over another element with respect to the criterion or property with respect to which they are compared to construct a $m \times m$ matrix, where m is the number of criterion being compared[77]. In Resilience Scenario, all the alternatives were compared pair-wise with respect to the objective, which was to maximize the network resilience. Similarly, in Efficiency Scenario; they were compared to maximize the efficiency of flow in the network. For example, in Resilience Scenario, it is assumed that algebraic connectivity *(λ_2)* is strongly preferred (4 times) over characteristic length *(l)* in maximizing network resilience. The pair wise comparison matrices for the two scenarios are shown in Table 5. The weights were assigned based on the relative importance of each metric in addressing the goal, i.e. maximization of resilience or efficiency, as evidenced from the published studies.

Table 5: Pair wise comparison matrix for the two optimization scenarios.

Resilience Scenario						**Efficiency Scenario**					
	L	c'_b	f_C	λ_2	r_m		l	c'_b	f_C	λ_2	r_m
l	1	1/3	1/2	1/4	1/2	l	1	2	2	2	2
c'_b	3	1	2	1/3	2	c'_b	1/2	1	2	1	2
f_C	2	1/2	1	1/2	1	f_C	1/2	1/2	1	1/2	1
λ_2	4	3	2	1	2	λ_2	1/2	1	2	1	2
r_m	2	1/2	1	1/2	1	r_m	1/2	1/2	1	1/2	1

The normalized principal Eigen vector of the pair wise comparison matrix provides the weighting matrix for the criteria. One important attribute of the decision making process in the AHP is the consistency of the estimator. In the instance of absolute consistence, the principal eigenvalue *(λ_{max})* would be equal to n. For general cases, absolute consistence is unrealistic to be achieved[78]. To address this issue, Saaty[76] proposed the consistency index *(CI)* as follows:

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad (10)$$

In the instance of absolute consistence, $CI=0$ and $\lambda_{max} = n$[76]. For all other cases, the level of inconsistency can be measured by the consistency ratio *(CR)*, defined as

$$CR = \frac{CI}{RI} \qquad (11)$$

where, *RI* or the random index, is the average value of *CI* for randomly generated reciprocal matrices using the Saaty scale (scale of 1-9). The weighting vector obtained is regarded as consistent iff $CR<10\%$. Weighting vectors obtained for the two scenarios are presented in Table 6.

Table 6: The weighting vectors obtained through AHP.

Metric	Scenario 1	Scenario 2
l	8.2%	33.9%
c'_b	20.7%	20.2%
f_C	15.8%	12.9%
λ_2	39.5%	20.2%
r_m	15.8%	12.9%
λ_{max}	5.20	5.10
CR	3.8%	2.2%

The MCA model combines the weights obtained from the AHP with the values to determine the overall utility of the alternative. This study uses the Weighted Summation *(WS)* approach, arguably the simplest and most widely used technique for this purpose. In the WS approach, the criteria are morphed onto a commensurate scale of 0 to 1, with 1 representing the best performance. The utility score or the INR value for each alternative is determined using Eq. 12.

$$u_i = \sum_{j=1}^{m} v_{i,j} w_j \qquad (12)$$

where, $\sum_{j=1}^{m} w_j = 1$ and $0 < w_j \leq 1$.

Results and Discussion

The utility scores obtained for each criterion for the alternate designs of AtN are presented in Figure 9. In the scenario of resilience maximization, i.e. scenario 1, alternate AtN4 performs the best while in the scenario of efficiency maximization; the original network layout has the best performance. In terms of overall best performance, AtN4 marginally edges out all other alternatives including the original configuration. This observation can be attributed to the role of one particular metric, the central-point dominance (c_b'), in its entirety. As discussed previously, while a higher value of c_b' indicates higher efficiency of flow within the network, increasing the resilience of the network structure entails a lower c_b'. This dictated the conversion of c_b' raw score to c_b' value for the two optimization scenarios.

The original configuration of AtN has the highest c_b' value of 0.28. Since the alternate configurations were developed with the goal to maximize the network resilience, all of them have significantly lower c_b' value. For example, AtN4 has a c_b' value 64% lower than the original configuration. Consequently,

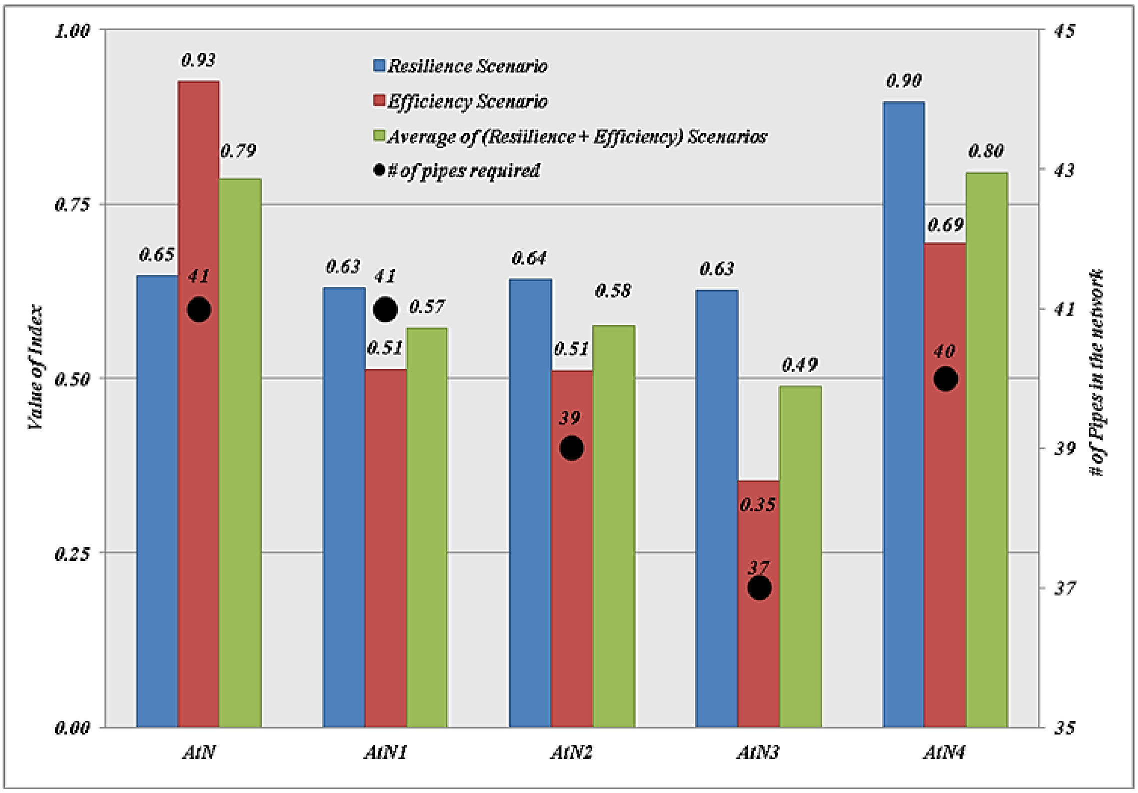


Figure 9: Plot of the index values for the alternate deigns under the two different scenarios. The index values are plotted in a scale of 0 to 1, where 1 represents the absolute best option.

when the value scores were developed for scenario 2, all alternate configurations scored lower on the value scale compared to the original configuration. Lowering the c_b' value is however critical in order to increase the robustness of the system. Water distribution systems have certain critical vulnerable nodes like the source nodes, failure of which can cripple the entire network. Designing a system which adds more critical nodes (in terms of stability) to the system proportionally would increase its vulnerability to be prone to more targeted attacks and would be an imprudent decision to make from the resilient perspective.

The algebraic connectivity (λ_2) has been assigned the maximum weight (~40%) in scenario 1. While critical ratio of defragmentation (f_c), meshedness coefficient (r_m) and algebraic connectivity(λ_2) all are related to the resilience of the network, f_c and r_m are directly proportional to the number of links in the network. Arguably, the stability and redundancy in a network can be increased by increasing the number of connections, i.e. the links, between the nodes. However, it also involves larger investment in terms of capital cost, material and energy which is not justifiable from the perspective of economics and sustainability. Conversely, λ_2 is dependent on the number of nodes, the number of links as well as the way in which nodes are connected, i.e. for a given number of nodes and links while f_c and r_m cannot be altered, different topologies would have different values for λ_2. Thus it offers a unique opportunity to increase the robustness and redundancy of a network by opting for better topologies rather than increased material and energy investment.

RELATIVE CRITICALITY INDEX (RCI)

In addition to the topological characteristics affecting the reliability of the distribution systems, non-topological characteristics play a significant part in determining the reliability of the system. However, including those non-topological characteristics in the network analysis would make the analysis significantly more complex, in particular for large systems. To account for the non-topological characteristics contributing to the reliability and vulnerability of the distribution systems, this study uses the relative criticality index (RCI), defined as the *"relative criticality per unit mile of different pipe types in the given system"* [79]. The relative criticality index (RCI) presents an overall criticality index of pipelines in water distribution incorporating the effects of reliability, cost and energy required for break repairs based on the pipe material as shown in the following equation [79]:

$$RCI_j = R_j(x) + C_j(x) + E_j(x)$$

where, x is the distribution system in discussion; $R_j(x)$ is the reliability component of pipe type j; $C_j(x)$ is the Cost function of pipe type j, and $E_j(x)$ is the Energy function of pipe type j. RCI would allow a better comprehension about the reliability of the distribution system based on the pipe material type and would allow to allocate resources according to the criticality and also aid in making more informed choices about the material at the time of system expansion or implementation.

Relative Dependency Index (RDI)

One of the characteristics unique to provisional infrastructure services, like water and energy provision; particular to the centralized model is that the entire system is hinged around a particular point, the failure of which renders the entire system non-functional. Elucidating further, in case of typical centralized water supply system; one central water treatment caters to a significant population, often to more than 50% of the total population of the urban area. In the unfortunate instance of failure of the treatment plant, the provision of potable water to all the residents dependent on that particular is disrupted. In the ideal scenario all the residents should have the option of obtaining potable water from more than one source, so that in event of one source failing the other source can still provide for the sustenance without interruption. An excellent example is furnished by the households which employ rainwater harvesting. Not only does that reduce stress on the centralized supply, it also provides them with an alternate source of supply. Unfortunately, however, this uniqueness cannot be incorporated into any of the indices discussed beforehand and hence a relative dependency index (RDI) is proposed. The RDI comprises of two metrics, (1) percentage of residents having dual source of supply *(ζ)*, and (2) the percentage of residents (in the urban area under purview) connected to the largest water treatment plant *(ξ)*, i.e. if a city is supplied by three different plants with each having a share of 50%, 30% and 20% respectively, then $\xi=0.50$. RDI is a weighted sum of ζ and $(1- \xi)$ with a greater weight assigned to ζ, since a higher proportion of people having access to multiple sources of supply increases the inherent redundancy of the system making it more resilient.

$$RDI = 0.75\zeta + 0.25\left(1-\xi\right)$$

THE COMPOSITE INDEX OF RESILIENCE FOR UWS (R-INDEX)

While the indices developed in Section 3.1 address the criticalities individually, a composite index has two distinct advantages over comparing these indices individually. Firstly, it allows the stakeholders to preferentially assign weights to each of these indicators to make the composite index more suited for their particular climactic, topographic and demographic conditions, i.e., semi-arid regions in the US Southwest might assign a significantly higher weight to IWS than the water rich Northeast US. Secondly, a single score index provides a comprehensive holistic quantification of the resilience of UWS allowing the decision makers to effectively compare across different alternatives.

The composite index of resilience for urban water systems, the **R**-Index can be developed through a weighted summation approach, where each of the indices are preferentially assigned an weight and the final form can be expressed as:

$$\begin{aligned}&\Re = \sum\left(\omega_1 \times IWS + \omega_2 \times WQI + \omega_3 \times INR + \omega_4 \times RCI + \omega_5 \times RDI\right)\\&iff\ \ IWS, WQI, INR, RCI, RDI > 0\end{aligned}$$

where, ω_1- ω_5 = weighting factors assigned through social decision making for a particular system.

One of the most popular methods of assigning weights to multiple criteria through a social decision making process for multi-criteria decision analysis is the Analytic Hierarchy Process (AHP) as proposed by Saaty[76]. However, AHP is built on the basic assumptions that the criteria being evaluated are functionally independent and can be arranged hierarchically. AHP is not suited for decision problems, like the one being evaluated in this study, where there exists interactions and interdependence of higher-level elements on a lower-level element. Problems of this category allow feedback among clusters forming a network system. Taking the current study as an example, it can be observed that many of the higher level elements like INR, WQI and RDI are all dependent upon or influenced by the layout of the distribution network, a lower level element. The Analytic Network Process (ANP), proposed by Saaty[80] addresses how to order a set of activities based on their relative importance in a multi-criteria decision problem taking into account these interdependencies and feedbacks among clusters. This study proposes the uses of ANP to determine the individual weights through feedback from a group of experts about the degree of interdependence among the criteria being considered.

TEMPORAL DIMENSION OF RESILIENCE

One other critical aspect of resilience is the temporal dimension, i.e. how quickly the system can recover from a failure, which is particularly emphasized in the engineering concept of resilience. While the index developed herein, quantifies the resilience of a system in terms of its capacity to absorb perturbations and still remain functional, it does not take the temporal dimension in to account. The temporal dimension of resilience is a function of the efficacy of resource mobilization which is not explicitly dependent on the system design and hence could not be incorporated within the **R**-Index. This study provides a novel way to estimate the temporal dimension of resilience for a system using the **R**-Index. Let the **R**-Index be plotted as a function of time, ***R****(t)*where the perturbation happens at time t_1, recovery is initiated at time t_2 and the system regains its original level of functionality by time t_3 (Figure 10). The *Severity of Failure* can be conceptualized as a function of the *Slope of Failure* and the *Depth of Failure*. The slope $\frac{d\mathbb{R}}{dt}$ between t_1 and t_2 is negative and is an indication of the *Severity of Failure*. The severity of failure is dependent on both system design and the magnitude of the perturbation. A more resilient system would be able to thwart more of the perturbation. Similarly, for a given system design, the severity of failure would vary with the degree of perturbation, i.e. an earthquake of magnitude 7.0 would cause a more severe failure than an earthquake of magnitude 4.0. Hence, efforts to minimize the *Severity of Failure,* is primarily governed by the design and planning phase through increased robustness and redundancy of the system. On the other hand, the slope $\frac{d\mathbb{R}}{dt}$ between t_2 and t_3 is positive and would indicate the *Speed of Recovery*, which is a function of the efficacy of information collection and resource mobilization.

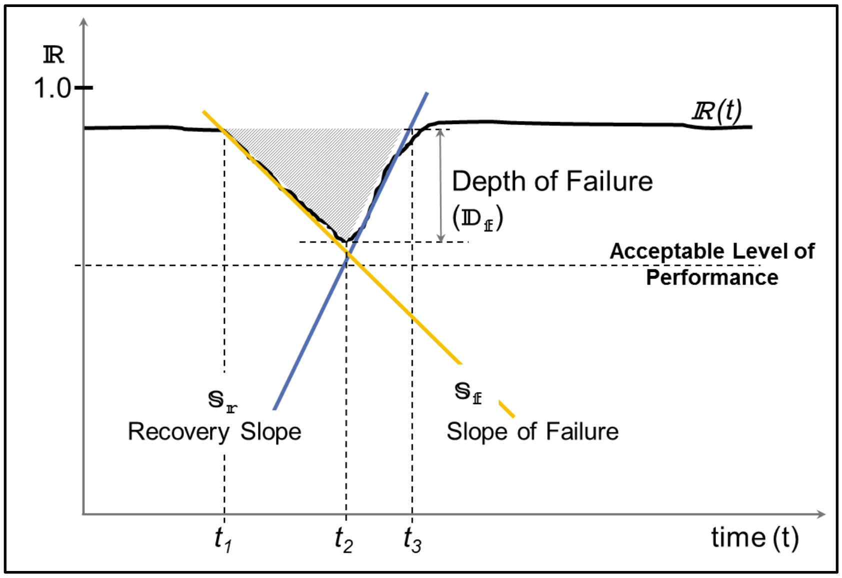


Figure 10: R-Index plotted as a function of time. The perturbation happens at time t_1, recovery is initiated at time t_2 and the system regains its original level of functionality by time t_3. The shaded area represents the *Total Failure* the system undergoes for the given event of perturbation.

The speed is recovery is primarily governed by operation phase of the system. A smart system, i.e. a system which can convey information back to the control centers through optimized placement of sensors would increase the speed of recovery and be able to minimize the total failure. A necessary condition for a system to be resilient is that $\frac{d^2\mathbb{R}}{dt^2} > 0$, i.e. there exists a local minimum which indicates the initiation point of recovery. Otherwise the system would exhibit a cascading pattern of failure without any probability of failure containment. While a resilient and adaptable system design would contain requisite inherent redundancy within the system design to prevent a pattern of cascading failure, to minimize the total failure and efficient mobilization of information and resources is crucial.

CHAPTER 4

EFFECT OF NETWORK TOPOLOGY ON WATER QUALITY IN THE DISTRIBUTION SYSTEMS

As described in Chapter 3, analyzing the physical distribution system as a complex network reveals certain implicit properties of the system, which are non-apparent otherwise. While there are numerous studies performed on modeling the water quality in the distribution systems, none of those studies explore the relationship between water quality and the topology of the system. This study attempts to explore that frontier and develops an empirical relationship between network metrics and water quality parameters.

For the purpose of this study, the pool of six network metrics, viz. (1) graph diameter, (2) characteristic path length, (3) central point dominance, (4) algebraic connectivity, (5) critical ratio of defragmentation, and (6) meshedness coefficient, has been narrowed down to two metrics: central point dominance and algebraic connectivity. The rationale for choosing these two metrics can be surmised as follows. Central point dominance (c'_b), which is a measure of the dominance of hubs in a network, is related to both efficiency and resilience of the network configuration. While a higher value of central point dominance facilitates flow in the network rendering a more economical design, it also makes the network more vulnerable compromising its resilience. This is attributable to the fact that a high c'_b indicates high sensitivity of the network around the central point(s). The aforementioned properties make c'_b a critical metric to be explored as the results obtained through his analysis can then be tied back to both the resilience and flow efficiency of the distribution system.

Algebraic connectivity (λ_2) is a surrogate measure of the resilience of the distribution system and is dependent on the number of nodes, the number of links as well as the way in which nodes are connected, i.e. for a given number of nodes and links while critical ratio of defragmentation and meshedness coefficient, two other measures of redundancy and robustness cannot be changed, different topologies would have different values for λ_2. Thus it offers a unique opportunity to increase the robustness and redundancy of a network by opting for better topologies rather than increased material and energy investment. The derivation details of these two metrics have been discussed in Chapter 3.

NETWORK METRICS AND RESIDENCE TIME

Previous studies have shown that distribution system water quality parameters, like residual chlorine concentration, disinfection by-product formation, microbial growth, etc. all exhibit strong correlations with the water age in the distribution system. This study developed 8 alternate configurations of the Anytown Network, including those developed for the previous studies. Hydraulic analyses of all eight alternate topologies were performed through

WaterGEMS to estimate the maximum residence time experienced at any point

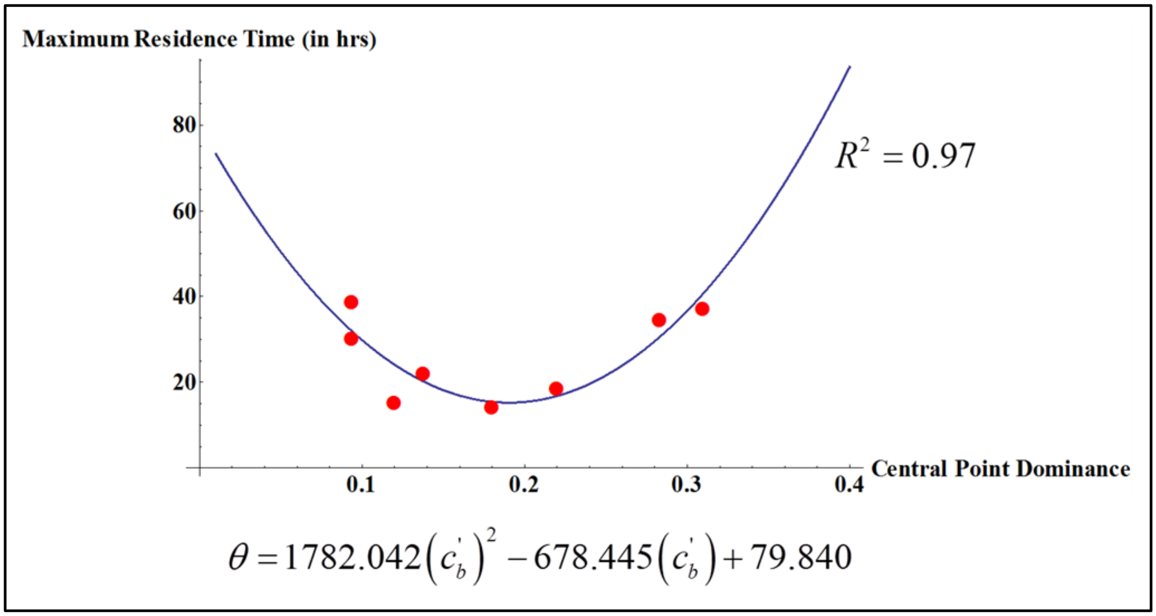


Figure 11: Maximum residence time in the distribution system plotted against the central-point dominance. The 'red' points indicate the observed values and the 'blue' line indicates the fitted line.

within the distribution network to assess the worst quality of water that can exist within the distribution system. Figures 11 and 12 show the relation between the maximum residence time experienced in the system with respect to central point dominance and algebraic connectivity respectively. The relations can be expressed as:

$$\theta_{\max} = 1782.042(c_b^{'})^2 - 678.445(c_b^{'}) + 79.480$$, and

$$\theta_{\max} = 120.887(\lambda_2) - 38.540$$

The parameters estimated to fit the model were all significant at $p<0.02$.

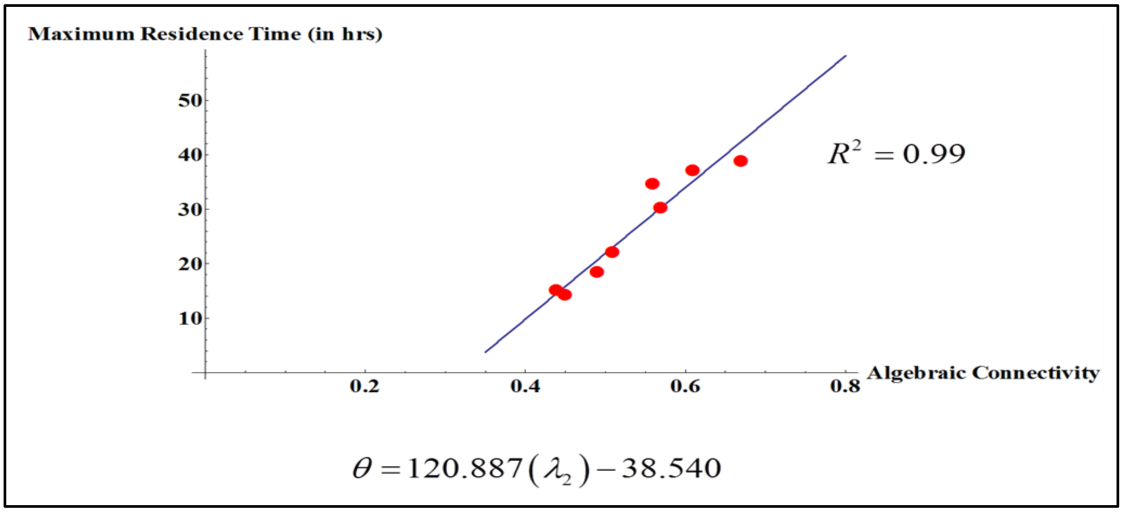


Figure 12: Maximum residence time in the distribution system plotted against the algebraic connectivity. The 'red' points indicate the observed values and the 'blue' line indicates the fitted line.

The results as obtained herein provide a few key insights. The results indicate that there exists a certain optimum value of c'_b, which minimizes the residence time within a distribution system (Figure 11). In addition, the results also indicate that the maximum residence time within a distribution system varies significantly with the c'_b value. A possible explanation for this phenomenon can be construed from the empirical observation in the following manner: With a very low c'_b value, the network topology approaches that of a purely random network. In that scenario water has to travel via many more nodes before it reaches the destination. This increases the residence time of water in the distribution system. This can be corroborated by the fact that a lower c'_b value represents a lower efficiency of flow within the network system. On the other hand, a higher c'_b value represents a more scale free network with centralized hubs in the system. Often, as evidenced from the alternate configurations generated for this study, this leads to longer pipe-lengths within the distribution network thereby increasing the maximum residence time.

For the relationship between maximum residence time and algebraic connectivity of the network, the results obtained in this study predict a linear relationship (Figure 12). The nature of this correlation can be attributed to the fact that increasing the algebraic connectivity increases both the robustness and the redundancy within the network system. For physical systems, this translates to water within the network going through more loops before it reaches its destination, thereby increasing the residence time within the network.

RESIDENCE TIME AND WATER QUALITY

This study uses a representative water quality parameter to assess the change in water quality with increasing time. The parameter chosen for this study is residual chlorine concentration. For residual chlorine concentration profile in the distribution system, this study assumes a first order decay model for chlorine, i.e.

$$C_t = C_0 e^{-Kt},$$

where C_t = concentration of chlorine at time t, C_0 = initial concentration of chlorine, and K = the decay constant. First-order decay model has been assumed for this study as the performance benefit of other dynamic models of chlorine decay over the first-order model has been found to be negligible[81]. The decay constant used herein is a function of the bulk decay-rate constant, wall decay-rate constant, molecular diffusivity of chlorine, the kinematic viscosity of water, flow velocity and the radius of the pipe[30,82]. The overall co-efficient for chlorine decay as used in this study can be expressed as[82]:

$$K = k_b + \frac{0.66\times10^{-4}u^{0.83}r^{-0.17}k_w}{0.33\times10^{-4}u^{0.83}r^{0.83} + rk_w} \text{ for } R \geq 2300$$

$$K = k_b + \frac{Ak_w}{Br^2k_w + \frac{1}{2}rA} \text{ for } R < 2300$$

where, k_b = bulk phase chlorine decay coefficient *(day^{-1})*, u = flow velocity *(ft/day)*, r = radius of the pipe *(ft)*, k_w = wall reaction constant *(ft/day)*, L = pipe length *(ft)*, $A = 4.75\times10^{-3}L + 9.23\times10^{-4}u^{0.67}r^{1.34}L^{0.33} + 0.27ur^2$,and $B = L + 19,458u^{0.67}r^{1.24}L^{0.33}$

The aforementioned overall coefficient of chlorine decay follows from the following reaction-rate expression:

$$\frac{dC}{dt} = -k_bC - \frac{k_wk_f}{r_h\left(k_w + k_f\right)}$$

where, k_b = bulk phase chlorine decay coefficient *(day^{-1})*, k_w = wall reaction constant *(ft/day)*, r_h = hydraulic radius of pipe (pipe radius/2) *(ft)*, and k_f = mass transfer coefficient of chlorine *(ft/day)*. The minimum chlorine concentration

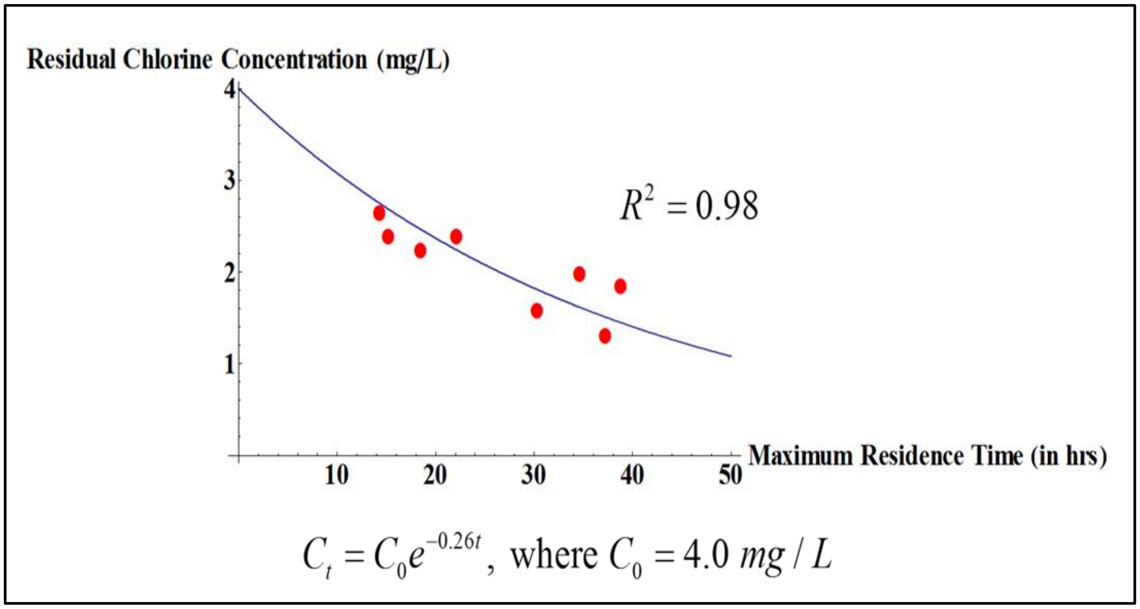


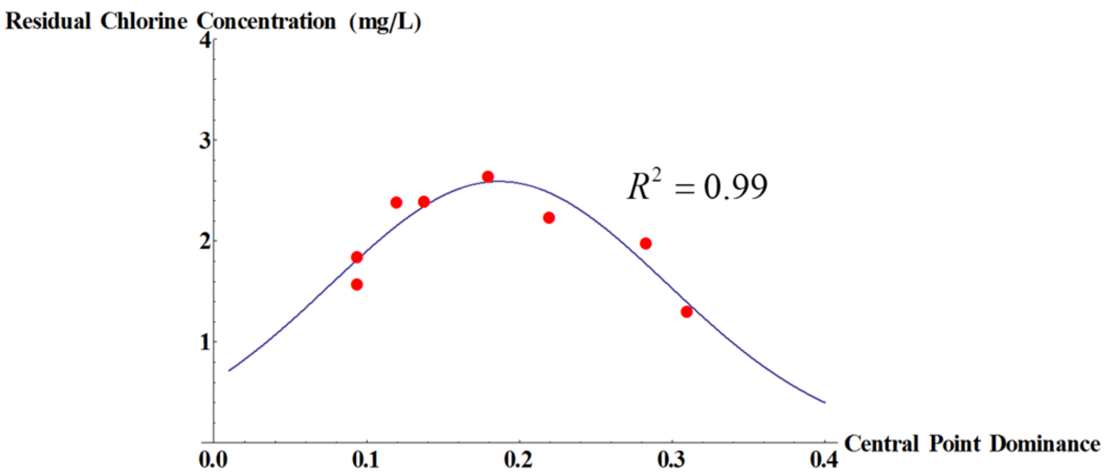
Figure 13: Residual chlorine concentration as a function of maximum residence time. The 'red' points indicate the observed values and the 'blue' line indicates the fitted line.

within the distribution system in mg/L was obtained through water quality modelling in WaterGEMS[83] (Figure 13). The decay rate constant was assumed to be the one provided by Clark et. al.[82] Assuming no re-chlorination and an initial residual chlorine concentration of 4.0 mg/L as incorporated in the WaterGEMS model, the observed values for minimum chlorine concentration are congruent to a first order decay within the distribution system as has been evidenced in previous studies[30,81,82,84]. The overall decay constant as observed in this study is 0.26 day^{-1}, which is congruent to the observed values for physical distribution systems[81,84–88]. Combining the observed trend for the minimum residual chlorine concentration within the distribution system with the network metrics (central point dominance and algebraic connectivity) through the observed maximum residence time, the following expressions can be developed (Figures 14 and 15).

$$C_t = C_0 e^{-1.35\left(30.34\left(c_b^{'}\right)^2 - 11.34\left(c_b^{'}\right) + 1.38\right)},\ \text{where } C_0 = 4.0\ mg/L, \text{ and}$$

$$C_t = C_0 e^{-0.58\left(4.07(\lambda_2) - 1.01\right)},\ \text{where } C_0 = 4.0\ mg/L$$

This study shows that the residual chlorine concentration in a distribution

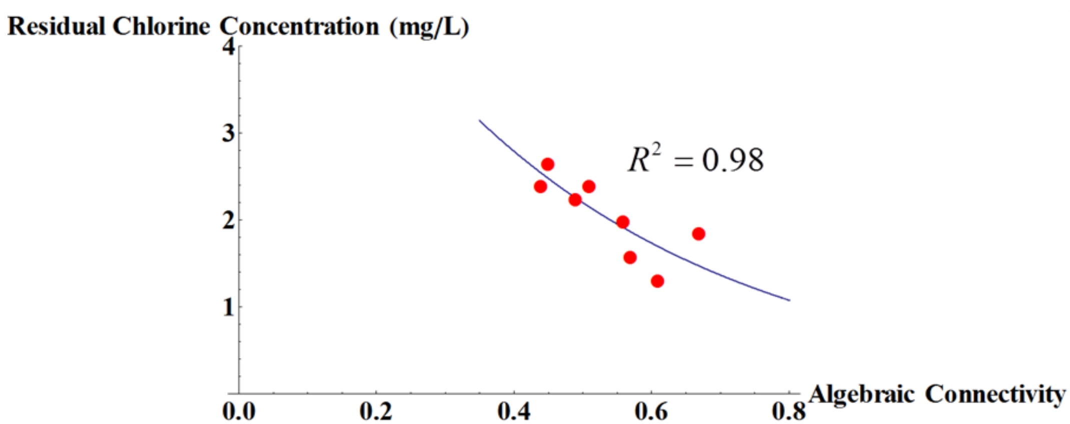


$$C_t = C_0 e^{-1.35\left(30.34\left(c_b^{'}\right)^2 - 11.34\left(c_b^{'}\right) + 1.38\right)},\ \text{where } C_0 = 4.0\ mg/L$$

Figure 14: Predicting residual chlorine concentration (minimum) through central point dominance. The 'red' points indicate the observed values and the 'blue' line indicates the fitted line.

network can be comprehensively predicted based on network properties of the distribution system. As discussed in Chapter 3, network metrics can predict the efficiency of flow within the network and the implicit resilience of the system based on the network topology. While there are numerous models and software that predict the flow efficiency and water quality within the distribution system, they are not able to provide any assessment of the system resilience. This study shows that network metrics can be used as comprehensive indicators to predict the resilience of, efficiency of flow within, and water quality in the distribution system network.

This study shows that in conjunction with hydraulic parameters of the



$$C_t = C_0 e^{-0.58\left(4.07(\lambda_2)-1.01\right)},\ \text{where } C_0 = 4.0\ mg / L$$

Figure 15: Predicting residual chlorine concentration (minimum) through algebraic connectivity. The 'red' points indicate the observed values and the 'blue' line indicates the fitted line.

distribution system, network metrics can be used to comprehensively characterize a distribution system including its flow efficiency, implicit resilience of the system in terms of increased redundancy and robustness and the water quality within the network system. This has a few distinct advantages over the current practice. First, it reduces the computational burden of the process of distribution system property determination. In conventional approach, we have to rely on multiple computational models to determine each of these system properties, like resilience, flow efficiency, and water quality. Second, having a single metric that can predict all the relevant system properties can prove to be consequentially advantageous in design and planning phase of the project.

CHAPTER 5

SUSTAINABILITY AND RESILIENCE: COMPLEMENTARITY OR TRADEOFF?

Prima facie there is a trade-off between sustainability and resilience. An oft-pursued solitary goal of sustainable development is 'reduction of material and energy use' in the implementation phase. Unfortunately, this notion is based on short-term thinking and fails to capture a holistic view of the lifetime of the project. Unidirectional pursuit of this goal would require reduction of material and energy investment to the maximal extent possible, which would undermine the resilience of the system by eliminating redundancy or taking out some of the energy and material investments that make the infrastructures more robust. However, in the long run, this approach would be, less sustainable; because once these UIS are exposed to a natural or anthropogenic hazard they will have a higher probability of failure owing to their low resilience and would need to be replaced. This entails a far greater need in material and energy investment than what would have been required to incorporate some degree of resilience into the UIS in the first place. In addition, a failure of the UIS would result in a service disruption and utility losses. But this leaves a very important unanswered question, how much more resilient should the UIS be. We attempt to show how planners can answer this question.

It can be shown that there exists a certain point of making UIS more resilient, where it is imprudent to increase resilience any farther because the total life-cycle sustainability starts to decline. Thus to minimize the total life-cycle material and energy use it is imperative that sustainability and resilience are pursued together as complementary attributes during the planning and design phase of UIS. The need for sustainable and resilient infrastructure is also emphasized by ASCE in their recent report about the state of America's infrastructure systems, which states: *"Infrastructure systems must be designed to protect the natural environment and to withstand both natural and man-made hazards, using sustainable practices, to ensure that future generations can use and enjoy what we build today, as we have benefited from past generations."*[89]

WHAT IS THE SUSTAINABLE AND RESILIENT (SURE) ZONE OF UIS PLANNING AND DESIGN?

The sustainable and resilient (SuRe) zone of UIS planning and design is defined as the zone where increased material and energy investment that increases the system resilience, increases the system sustainability over the life-cycle of the UIS. To illustrate this concept, we determined the seismic performance of a potable water distribution system of a hypothetical city with a population of 1 million. The city is located somewhere between 35°N-40°N and 120°W-125°W, which approximates the location of San Francisco-Santa Barbara region in the state of California. The location choice was partly influenced by the recent efforts undertaken in Alameda County, CA to seismically retrofit their entire potable water system through a public-private partnership by modestly raising the water bill of their customers[90].

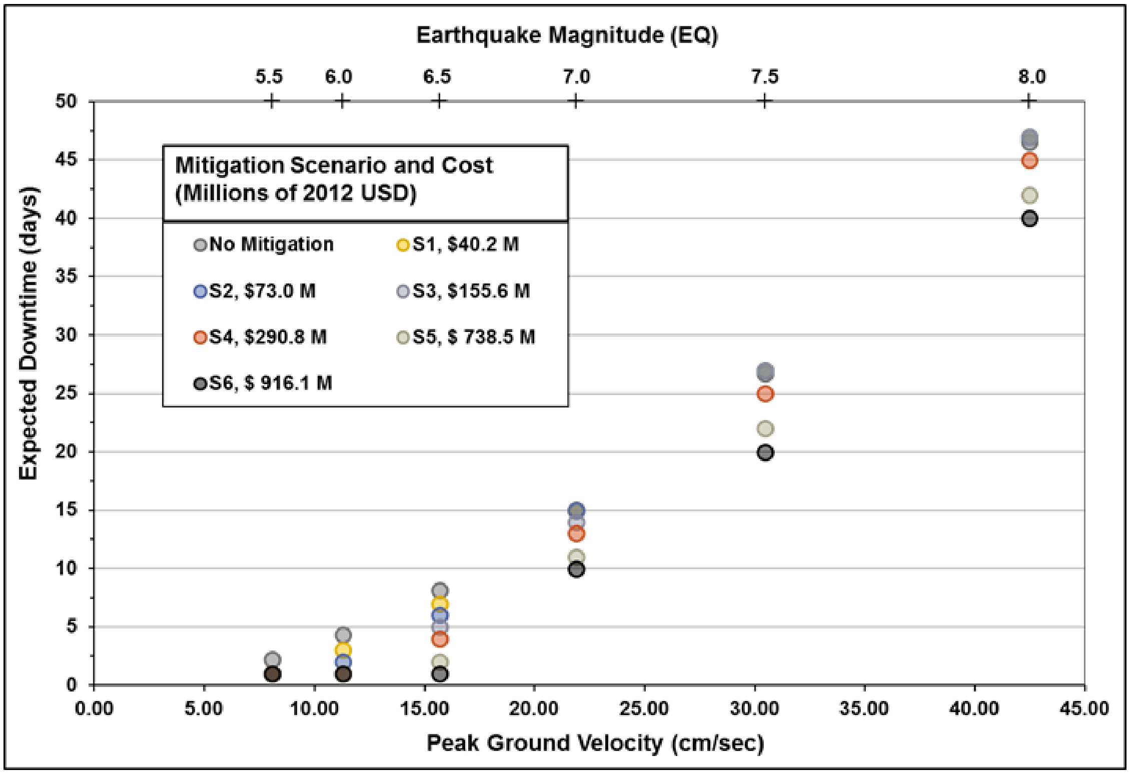


Figure 16: Cost of seismic retrofit of the potable water system for a million residents of a hypothetical located within the coordinate of 35°N-40°N and 120°W-125°W.

Note: The horizontal axis at bottom shows the Peak Ground Velocity (PGV) in cm/sec, and the horizontal axis at top shows the corresponding Earthquake Magnitude (EQ)

Six hypothetical seismic retrofit scenarios were developed, which progressively reduce the expected downtime[5] of the utility in case of an earthquake (EQ). Figure 16 show the down time for a particular EQ intensity and retrofit cost, which includes both capital and operational costs. Previous

[5] 'Downtime' is conceptualized as the number of days the system remains non-functional, partly or fully, in the event of an earthquake.

studies exploring the relationship between pipeline damage and EQ have presented empirical relationships based on historical damage data[91–93]. For this study the empirical correlation obtained by Toprak et al.[93] was used. The expected downtime (days) were calculated based on the number of repairs required and the time needed to fix each of the repairs. It was assumed that the average time required for each repair, which includes both major and minor repairs; progressively increases with the magnitude of EQ (Table 7).

Table 7: Mitigation Scenarios and Expected Downtime (ED) in days

Magnitude	PGV (cm/s)	Average Hours Required/ Repair	Expected Downtime in Days						
			No Mitigation	S1	S2	S3	S4	S5	S6
5.0	5.80	0.4	1	1	1	1	1	1	1
5.5	8.09	0.4	2	1	1	1	1	1	1
6.0	11.27	0.5	4	3	2	1	1	1	1
6.5	15.70	0.6	8	7	6	5	4	2	1
7.0	21.88	0.7	15	15	15	14	13	11	10
7.5	30.48	0.9	27	27	27	27	25	22	20
8.0	42.49	1.0	47	47	47	47	45	42	40

Furthermore, it was also assumed that with increasing severity of EQ more resources would be mobilized to keep the time required to repair the

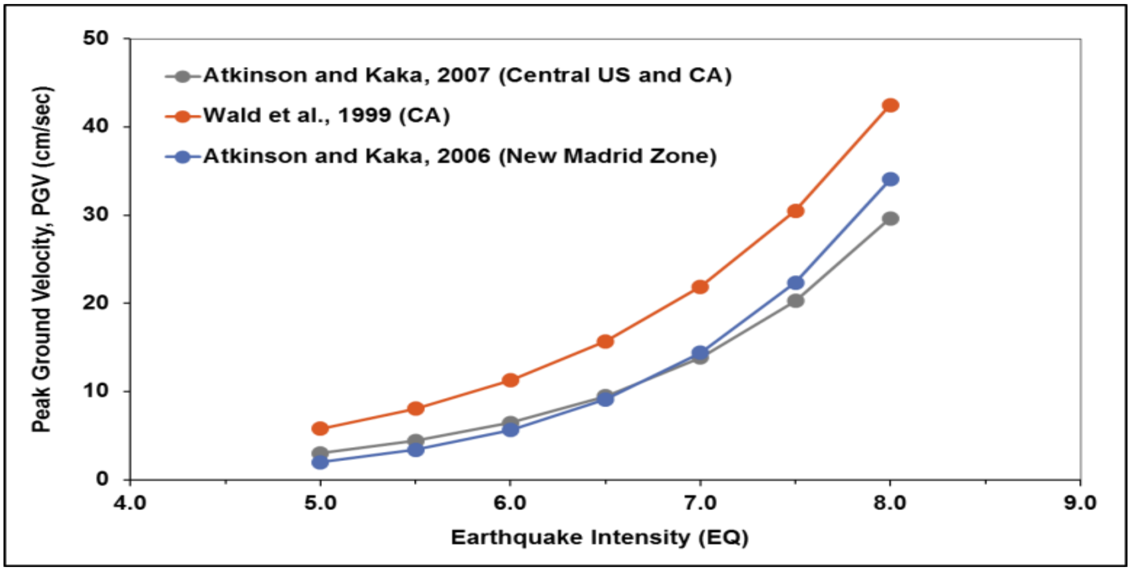


Figure 17: Empirical correlation between peak ground velocity (PGV) and Earthquake Intensity (EQ).

damage to a minimum. It should be noted that the No Mitigation scenario indicates the expected downtime in days for a single occurrence of the EQ of a particular magnitude. Also, EQ of magnitude 5.0 was excluded from further analysis since there is no change in ED due to mitigation efforts. The relation between EQ magnitude and PGV was estimated from a study of Wald et al. 1999, which developed an empirical relation between observed EQ magnitudes and PGV[94–96] (Figure 17). This study was chosen as it was California specific and provided the worst case scenario among the studies considered for this effort.

The expected downtimes were calculated based on the empirical relations between the number of pipe repair(s) required per unit length of pipeline and the peak ground velocity (PGV)[6], which have been observed at this location[91–93]. While the EQ magnitude is the most generic parameter that is used to describe the EQ intensity, it does not convey some very essential information like the EQ point-of-origin, the subsurface condition, etc., all of which are crucial in estimating its potential for damage at any given location. Research has shown that PGV provides the best relationship with damage. Hence, it was used for this case-study[97]. The relation between PGV and the EQ magnitude is dependent on the particular subsurface composition of the area and the distance between the point-of-origin of the earthquake and the location. The empirical correlation that used in this study was obtained from a study conducted by Wald, et al., for the region[94].

COST-BENEFIT ANALYSIS: THE ECONOMIC PERSPECTIVE

Traditionally, the feasibility of designing and planning a UIS to increase its resilience is governed by a benefit-cost analysis (BCA). And an UIS project is feasible only when the benefit-to-cost ratio is greater than 1. Herein, a BCA was performed for all the six mitigation scenarios that are shown in Figure15. The construction cost associated with seismic retrofit for different EQ damage potentials were estimated from a study done by Eidinger[98], which turns out to

[6] Peak Ground Velocity expresses the peak of the first integration of the acceleration record, where *acceleration* indicates the intensity, i.e. how hard the surface shakes in a given geographic area for a given earthquake.

match the costs of a recent retrofit that was undertaken by East Bay Municipal Utility District (EBMUD).

As shown Figure 16, that even with an investment of close to a billion dollars; the system is expected to experience considerable downtime in the event of an EQ with a very large damage potential. A cost-benefit analysis was

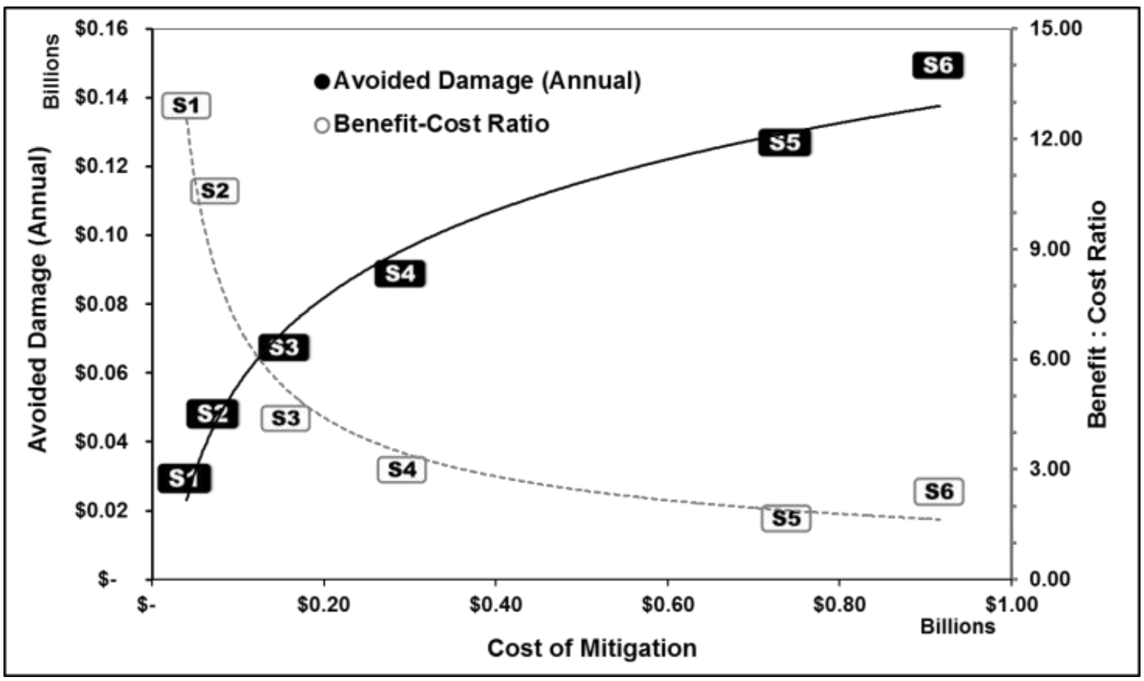


Figure 18: Benefits obtained from seismic retrofit of the potable water system, quantified in terms of economic value of avoided damage on an annual basis.

performed for the different mitigation scenarios using the Federal Emergency Management Agency (FEMA) BCA V4.8 toolkit[99], assuming a useful project life of 50 years, a discount rate of 5% and a utility loss rate of $103.00/capita-day for every day of downtime[7]. The benefits were assessed by calculating the damages

[7] A detail BCA performed by the FEMA BCA tool is a requisite condition for any pre-emptive hazard mitigation retrofit that requires Federal economic assistance for the project.

that were avoided. The reduction of probable downtime is estimated by considering the probability of occurrence of all EQs of different magnitudes within the useful lifetime of the project. The total down time is the sum of all the downtimes that are associated with those occurrences. As shown in Figure 19, if we increase our investment in mitigation, then the avoided damage increases at first then plateaus. In other words, to retrofit the system for low-probability high-damage potent EQs, the benefits or avoided damage do not increase that much after an investment of ~ $300 million. While all of the retrofit scenarios yielded a benefit-to-cost ratio greater than 1, it can clearly be observed that beyond a certain point, seismic retrofits to mitigate EQs with a larger damage potential, yields a dramatic reduction in BC ratio.

Cost-Benefit Analysis: The Sustainability Perspective

While the method of economic CBA is an established tool, there is no tool currently available which would allow the decision-makers to assess the cost-benefit of a project from the perspective of sustainability. The SuRe methodology introduced in this paper would provide a clear understanding about where the trade-off lies and be able to recommend the optimum options which are both sustainable and economically feasible. From a sustainability perspective, we need to reduce the total impacts over the entire life-cycle of the project and determine what level of retrofit gives the greatest return.

In an attempt to answer that question, an environmental BCA was

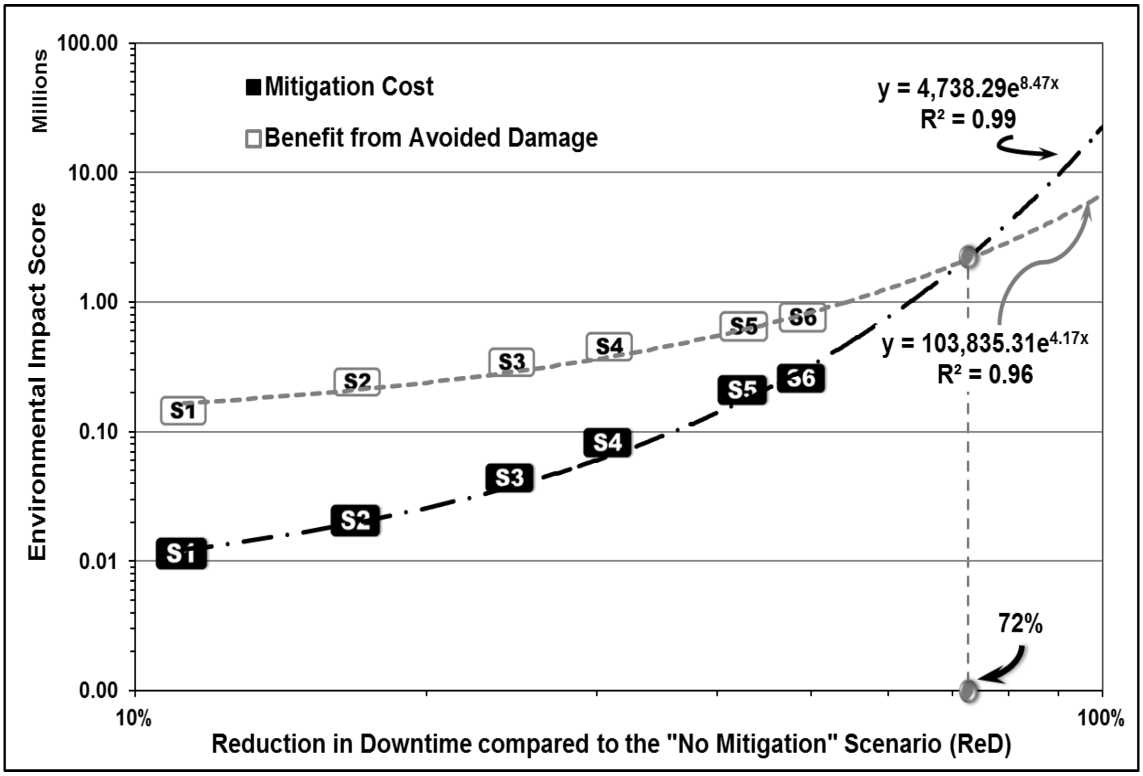


Figure 19: Cost-Benefit Analysis (CBA) of Environmental Impact Assessment (EIA). The EIA curves for both cost and benefit exhibit strong correlation with the level of ReD attempted in a retrofit scenario.

performed for the six different mitigation scenarios. A life-cycle impact assessment was performed on the economic value of both the mitigation cost and the corresponding benefits obtained in the form of avoided damage. The environmental impacts of the different economic values were estimated utilizing the Economic Input-Output Life Cycle Assessment (EIO-LCA)[8] tool[100]. The emission outputs were obtained for the different cost and benefit scenarios using EIO-LCA and TRACI (Tool for the Reduction and Assessment of Chemical and

[8] EIO-LCA estimates the energy and materials required for and the emissions resulting from any particular activity throughout the economy including the entire supply chain associated with the activity.

Other Environmental Impacts) output[101]. TRACI is a set of environmental impact categories emerging from the effects of different process-related emissions to land, water and air, as developed by EPA. The retrofit impacts (both in terms of costs and benefits) are provided in Appendix B. The impacts for each category were then divided by the average emissions that are caused by an average US person. These are classified into two broader categories: (1) *'Impact to Human Health'* and (2) *'Impact to Ecosystem'*. These two categories were then preferentially weighed according to the Hierarchist perspective, which weighs the Human Health and Ecosystem equally, assigning 50% weight to each of these catergories[102]. The reference values for and the weights assigned to the different categories are shown in Table 8.

Table 8: Emission categories as obtained from EIOLCA with the corresponding reference values and the preferential weights assigned to each category from a Hierarchist perspective. The categories obtained from EIOLCA were further grouped into 'Impact to human Health' and 'Impact to Ecosystem Health' category.

Impacts	Reference Value (t/cap-year)	Impact Category	Assigned weight
Global Warming (t CO_2 Eqv.)	24.52	Human Health	9.0%
Acidification (t H^+ Eqv.)	7.45	Ecosystem Health	16.0%
Human Health Criteria (t PM10 Eqv.)	0.08	Human Health	9.0%
Eutrophication (t N Eqv.)	0.02	Ecosystem	16.0%

Impacts	Reference Value (t/cap-year)	Impact Category	Assigned weight
		Health	
Ozone Depletion (t CFC-11 Eqv.)	0.0003	Human Health	9.0%
Smog Formation (t O_3 Eqv.)	0.12	Human Health	9.0%
Ecotoxicity (t 2,4 D Eqv.)	0.07	Ecosystem Health	16.0%
Human Health-Cancer (t Benzene Eqv.)	0.0003	Human Health	10.0%
Human Health-Non-Cancer (t Toluene Eqv.)	1.47	Human Health	8.0%

The environmental impact BCA was performed based on the ReD (Reduction in Downtime), defined *as the percentage of reduction in downtime achieved by a particular retrofit scenario over the lifetime of the project compared to the 'No Mitigation' scenario*. ReD is calculated by considering the EQ magnitude, the probability of its occurrence and the downtime associated with each EQ event. The different mitigation scenarios considered herein and their associated ReDs are shown in Table 9.

Table 9: Calculation of Reduction in Downtime (ReD) for different mitigation scenarios over the lifetime of the project compared to the "No Mitigation (NM)" Scenario

Magnitude	Probability of Occurrence	Number of EQ	Probable Downtime over the entire lifetime of the project (days)						
			NM	S1	S2	S3	S4	S5	S6
5.5	1.00	42.82	95	43	43	43	43	43	43
6.0	0.90	38.54	167	116	77	39	39	39	39
6.5	0.70	29.98	245	210	180	150	120	60	30
7.0	0.50	21.41	320	321	321	300	278	236	214
7.5	0.25	10.71	286	289	289	289	268	236	214
8.0	0.04	1.71	81	81	81	81	77	72	69
Total		188	1193	1059	991	901	824	684	608
Reduction in Downtime over the lifetime compared to the "No Mitigation (NM)" Scenario (ReD)			**0%**	**11%**	**17%**	**25%**	**31%**	**43%**	**49%**

The Environmental Impact Score (EIS) for the costs of and benefits obtained from each retrofit scenario are shown in Figure 19. It might be noted that the EIS reports the impact in terms of the average impact of an US person over a year. To elucidate further, the following example can be considered. Suppose for performing a certain activity, the EIS score is 1 million which is equal to the number of residents in this study. The EIS can be interpreted as: performing that activity caused annual emissions equivalent to the emissions caused by 1 million average US persons over the course of a year. Now if this activity was performed for 1 million people, then that activity increased their annual emission footprint by 100%. Figure 19 displays that though both the cost and benefit EIA increase exponentially with increasing ReD and the mitigation cost curve has a higher exponent value. According to this study, the environmental impacts arising from the retrofit efforts outweigh the benefits of avoided damage for ReD greater than 72%.

While the EIA curves for retrofit cost and associated benefits provide us with the a particular ReD value beyond which the impacts from the investment in retrofit outweighs the benefits from damage avoidance, it does not provide an optimum zone of planning and design where both sustainability (measured as net environmental benefit) and resilience (measured as ReD attainment) can be optimized together. A plot of net environmental benefit in terms of EIS against attainment of ReD generates the SuRe curve (Figure 20), which provides a clear indication about the sustainable and resilient zone of UIS planning and design. The following points can be inferred from Figure 20:

- The attainment of ReD beyond a particular point is counterproductive from the perspective of sustainability (55% in this instance).
- The slope of the SuRe curve varies with ReD attainment and is characterized by three distinct phases:

1. **Phase I** *(low resilience)***:** increases in resilience do not significantly improve sustainability (10%-~30% ReD);

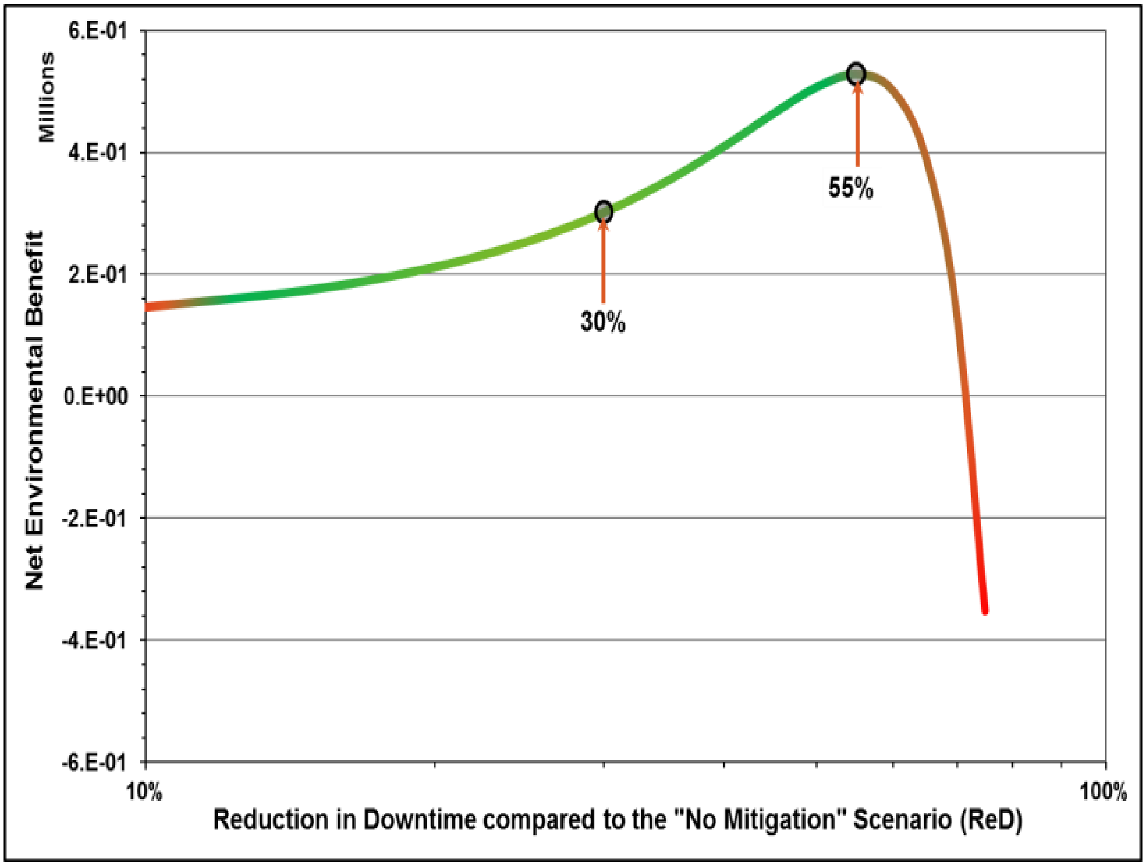


Figure 20: The SuRe Curve. It is characterized by three distinct phases based on the correlation between attainment of ReD in a retrofit and Net Environmental Benefits.

2. **Phase II** or the **SuRe zone** *(intermediate resilience)***:** increases in resilience greatly increases the sustainability (30%-55% ReD); and
3. **Phase III** *(high resilience)***:** increases in resilience results in a rapid decline in overall sustainability (>55% ReD).

The concept outlined herein and the case study provides us with a few key insights. First, while there is an apparent trade-off between sustainability and resilience, in the sense that increasing resilience warrants increased material

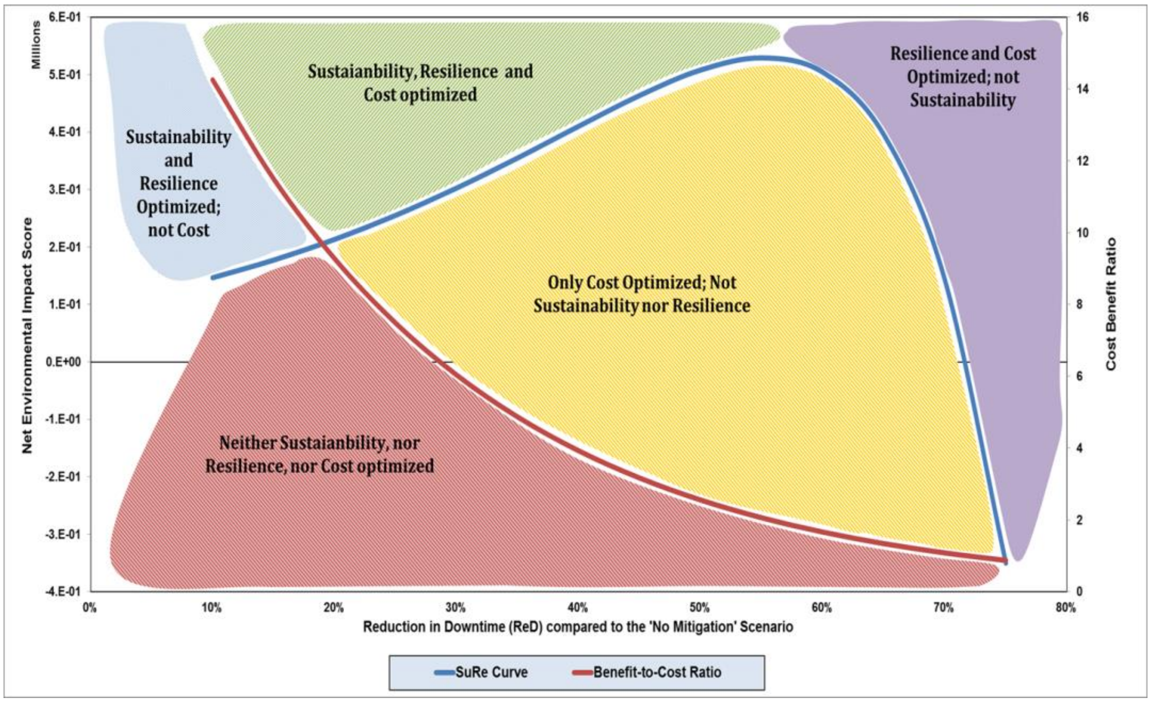


Figure 21: Optimization of Sustainability, Resilience and Cost

and energy investment. In actuality they are complementary when conceived holistically from a life cycle perspective. Second, there indeed exists a zone of planning and design, the SuRe zone, where both sustainability and resilience can be optimized together. However, it must be noted that this zone is not universal either across the spectrum of infrastructure sectors or spatially. Actually, this zone needs to be identified for different infrastructure sectors and for varying topographic and demographic conditions. These zones will become more refined and accurate as applications of SuRe curves proliferate. Once these curves are developed for different infrastructure sectors across diverse topographic areas, they can be used as a standard guideline for sustainable and resilient UIS planning and design.

Furthermore, if the economic BCA curve is combined with the SuRe curve, it is possible to identify the zones of planning and design where sustainability, resilience and cost, all of them can be pursued together (Figure 21). A plot would enable us to identify the UIS design which satisfies all the criteria of sustainability, resilience and cost. It would also give us a clear indication about the potential tradeoffs, if any; that exists between these criteria and the stakeholders can choose the alternative that matches their priorities.

CHAPTER 6

MAJOR CONSCLUSIONS AND FUTURE WORK

MAJOR CONCLUSIONS

The major conclusions that can be inferred upon from this study are as follows:

- Urban infrastructure systems act and operate analogous to ecological systems.
- Urban infrastructure systems are interconnected and more efficiency at the system level can be achieved by looking at the interconnections using a system level approach.
- Urban infrastructure systems exhibit characteristic dynamic-adaptive cycles analogous to ecological systems.
- The resilience index addresses resilience of urban water systems in both the short-term, i.e. its capacity to withstand shocks like earthquake, pipe-breaks, etc. as well as and long-term resiliency, like the capacity of the system to cope up with increasing population or a gradually changing climate pattern.
- The novelty of the resilience index developed in this study is that it can be adopted to quantify resilience of any urban infrastructure system, or for any other dynamic adaptive systems.

- The inherent resilience of an infrastructure system can be increased by altering its topology without any additional material and energy investment.
- Network metrics can be used to predict the resilience, efficiency of flow and water quality in the distribution network.
- Sustainability and Resilience are complementary when conceived holistically from a life cycle perspective.
- There indeed exists a zone of planning and design, the SuRe zone, where both sustainability and resilience can be optimized together.

FUTURE WORK

Future work in this genre should attempt to address the following issues:

- Development of a suite of infrastructural symbiosis models to better understand the urban infrastructure systems at the system level.
- Use infrastructural symbiosis models to capture the macro-level emergent properties (both benefits and problems) that arise from the interaction between the different components at the micro level.
- Understanding the cross-scale dynamics within urban systems and how that confers sustainability and resilience to the urban systems.
- Expanding the $\mathbb{R}$-Index for other infrastructure sectors by identifying the criticalities associated with each of those infrastructure sectors and

identifying (or developing, if need be) indexes that address those criticalities.

- Test the index of resilience as developed herein for physical systems that are in operation or are planned to be developed.
- Use real time data from physical systems to empirically corroborate the relations between the network metrics and water quality parameters as developed herein theoretically.
- Explore other network metrics, including but not limited to, network controllability metrics to assess their efficacy in describing system characteristics for physical infrastructure networks.
- Develop SuRe curves for other types of hazards for other geographical locations and for multiple infrastructure systems.

APPENDIX A: EDUCATION MODULE

TARGET PLOTS FOR ENVIRONMENTALLY RESPONSIBLE SELECTION OF CHEMICALS

Arka Pandit, Sergiy Smetana, and John C. Crittenden

Abstract

The number of registered chemicals is reaching 65 million according to the chemical abstract service (CAS). The United States Environmental Protection Agency (EPA) and Center for Disease Control and Prevention (CDC) has examined around 0.1 – 0.2 % of them for their toxicity. The synthesis of new chemicals requires fast screening method to determine their impact on the environment before they are used in commerce. The Office of Pollution Prevention and Toxics of EPA developed a number of models, which estimate the physical properties and potential environmental hazards. This education module presents a graphical tool that estimates of the chemicals fate and toxicity.

Keywords: Target Plots, Sustainable Chemicals,

1. Introduction

When we think about chemical use, we realize that we can divide the chemical usage into two categories: "things" and "stuff". We say this tongue in cheek but “stuff” is basically the chemicals and “things” are goods such as textiles, car parts, coating etc. This module will focus on “stuff”.

As of 2012, there are more than 2,200 high production volume chemicals (1million pounds/year) in US commerce according to the U.S. Environmental Protection Agency (EPA) (http://www.epa.gov/hpv/). Among the 64,443,421 chemicals registered in Chemical Abstracts Service (as of March 20, 2013, http://www.cas.org/content/counter), information on chemicals toxicity, bioavailability, ecosystem and human health toxicity is available only for 0.2 % of these chemicals through the Registry of Toxic Effects of Chemical Substances (RTECS), which includes more than 160,000 chemicals (http://www.cdc.gov/niosh/rtecs/RTECSfeatures.html). At the same time, chemicals usage has increased and this has led to new products and created business opportunities. Understanding the hazards associated with the emerging chemicals requires long term detailed research, which makes the comparison between chemicals of same functionality complicated for the manufactures to identify the best chemical for a given product. The availability of a fast tool to compare the characteristics and potential impacts of two chemicals would be a helpful tool for the product designers. A simple, but effective technique could be used to compare relative safety and sustainability of different chemicals. We present a graphical representation of numerous factors on a target plot or radial diagram that will allow one to select the most environmentally responsible chemical from several options. Such diagrams are widely used for a quick comparison of multiple factors. For example, “wind roses” are used to represent the dominant wind directions for a given time period (Figure 1).

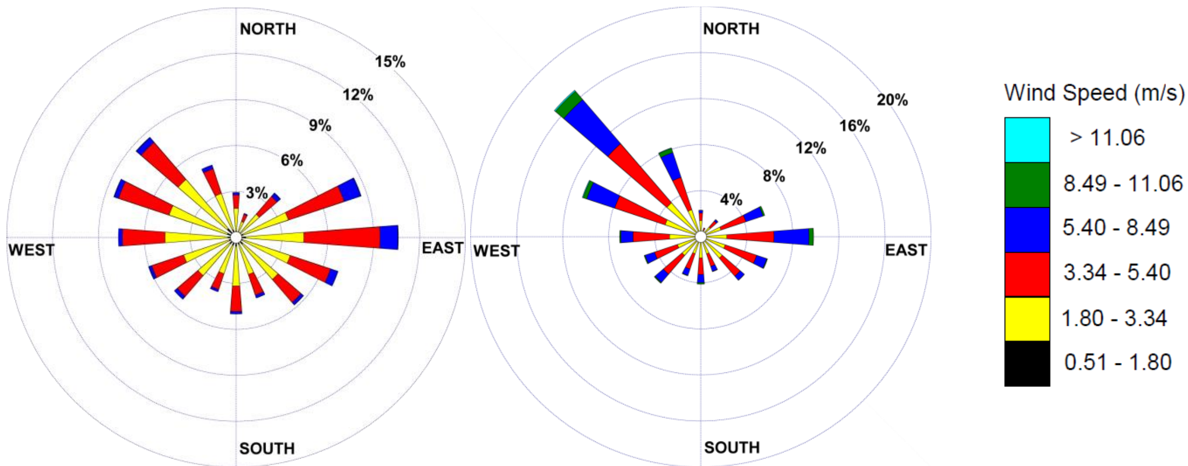


Figure 1. Wind Roses for August (left) and December (right) 1961 (Atlanta, GA, USA) Retrieved from: http://www.wcc.nrcs.usda.gov/ftpref/downloads/climate/windrose/georgia/atlanta/

Construction of a target plot requires three steps: (1) creation of a plot that includes the chemical properties of interest (e.g., toxicity, solubility, fate in the environment, etc.), (2) determination of these properties, and (3) plotting the results. These steps are easy for the common chemicals for which the chemical properties are known. For others, chemical properties can be determined from Pollution Prevention Framework (P2 Framework), which the U.S. Environmental Protection Agency (EPA) Office of Pollution Prevention and Toxics (OPPT) has developed. The P2 framework is a set of screening-level methodologies that use the structure of chemicals to evaluate their fate in the atmosphere or biosphere. It is based on multiple numerical models which assess a particular characteristic of a chemical and the probable influence the chemical might exert on environment or human health (http://www.epa.gov/opptintr/sf/pubs/p2frame-june05a2.pdf).

The tools were developed in response to the passage of the Toxic Substances and Control Act of 1970 (TSCA). TSCA was passed to prevent the release of chemicals into commerce that may cause harm to human health or the environment. TSCA gives EPA 90 days to decide whether a chemical is safe; consequently, EPA developed these tools to make a preliminary assessment. If the assessment shows that a given chemical may be harmful, then EPA will require further testing which may include animal testing. In such cases, a chemical manufacturer would most likely not test the chemical and not produce it.

There are two main categories when it comes to chemical users: formulators and chemical manufacturers. Formulators use chemicals to produce products like Personal Care Products. Manufacturers actually create new chemicals. OPPT developed the P2 frame work to allow formulators and manufactures to select and make more environmentally responsible chemicals, respectively.

The P2 framework contains thirteen programs/software tools that are incorporated in a single interactive EPI Suite. These software tools could be used separately or as a suite for a comprehensive evaluation of a chemical. Each software tool estimates one chemical property. The software tool, **AOPWIN,** estimates atmospheric oxidation rates of a chemical and provides half-lives for organic compounds based upon average atmospheric concentrations of hydroxyl radicals and ozone. The software tool, **BCFBAF,** estimates the bio-concentration factor for fish using the log of the octanol-water partition coefficient and biotransformation rate of a chemical in fish. The bioconcentration factor (BCF) compares the compound concentration in fish as compared to the water concentration for uptake by gills and skin of the fish. The BCF has been determined experimentally for 13200 organic compounds (13) and these data demonstrate that the tool can predict the BCF. This tool however does not estimate the potential of the chemical to migrate or accumulate through the food chain, which is referred to as bioaccumulation or biomagnification. The software tool, **BioHCwin,** calculates the biodegradation rate in the environment and reports the half-live of the chemical. The software tool, **BIOWIN,** determines the biodegradability of a compound in a wastewater treatment plant for both aerobic and anaerobic conditions. It is evaluated for the mixed populations of microorganisms. The software tool, **ECOSAR,** estimates the aquatic toxicity of a chemical. It calculates both the lethal dose 50% and lethal concentration 50% (LD50, LC50)for fish (96 hours of exposure), daphnia (48 hours of exposure), mysid (96 hours of exposure), green algae (72 or 96 hours of exposure), and earthworm (LC50, 14-days exposure). It also calculates the chronic value effects on mentioned organisms (the geometric mean of no observed effect and the lowest observed effect concentrations, observed for 21 day of exposure). Toxicity to fish, aquatic invertebrates, and algae are used to predict toxicity to a general aquatic community. The software tool, **HENRYWIN,** estimates Henry's law constant of organic compounds at 25°C. The Henry's constant can be used to determine the equilibrium concentrations in the air given the water concentration. The Henry's constant is important for determining the fate of the compound. For example, if a chemical will be transported in air, water or remain in both phases. The software tool, **HYDROWIN** calculates the aqueous hydrolysis rates (acid- or base-catalyzed), and can be used to calculate hydrolysis half-lives at a selected pH. The software tool, **KOAWIN,** estimates the octanol-air partition coefficient (the ratio of a chemical's concentration in octanol to the concentration in air at equilibrium). It is used to predict the partitioning (ratio of the chemical's concentration) in environmental media such as fish, soil, vegetation, hydrosol and aerosols, water or air. The software tool, **KOCWIN,** estimates soil sorption coefficient (Koc) – "the ratio of the amount of chemical sorbet per unit weight of organic carbon in the soil or sediment to the concentration of the chemical in solution at equilibrium" (12).The software tool, **KOWWIN,** estimates octanol-water partition coefficient which is related to the solubility in fat (lipophilic substance) and the hydrophobicity of a substance.

Accordingly, **KOWWIN** will allow one to estimate the biomagnification of the chemical. Biomagnification is the increase of a chemicals concentration in the biota which accumulates with increasing trophic levels and it accumulates with increasing fat solubility. The software tool, **MPBPVP**, estimates these physical properties of a chemical: melting point, boiling point, and vapor pressure. The software tool **WSKOWWIN** estimates water solubility of a chemical using ocatanol-water partition coefficient, which is calculated from **KOWWIN**. **WATERNT** is another software tool for water solubility estimation, but it is based quantitative structure activity relationships (it breaks down organic compounds into fragments and then adds up the contribution of each fragment on the organic compounds solubility). Obviously, taken together, these chemical properties would be very important to determine the fate and impact of chemicals in the environment.

Accordingly, the P2 Framework provides chemical impacts in 4 main categories: Physical/Chemical Properties; Hazards to Humans and the Environment; Chemical Fate in the Environment; and Exposure and/or Risk (Table 1). These areas are represented as scales on target plots. The P2 Framework could be used in both cases whether precise physical property data is available or not.

Table 1. Categories and outcomes of software tools within P2 Framework (http://www.epa.gov/opptintr/sf/pubs/p2frame-june05a2.pdf)

Physical/Chemical Properties	Hazard to Humans and the Environment	Chemical Fate in the Environment	Exposure and/or Risk
• Melting point • Boiling point • Vapor pressure • Water solubility • Henry's law constant • Soil organic carbon adsorption	• Carcinogenicity potential • Aquatic toxicity • Non-cancer human health effects	• Atmospheric oxidation potential • Hydrolysis • Biodegradation • Bioconcentration and bioaccumulation • Percent removal in wastewater treatment • Percent in each media (air, soil, sediment and water) • Persistence	• Consumer dermal exposure • Consumer inhalation exposure • Chemical concentrations resulting from discharges to surface water • Workplace releases and exposures

For the comparison, we used EPI Suite v4.11, which contains a number of Quantitative Structure–Activity Relationship (QSAR) software tools mentioned above (http://www.epa.gov/oppt/exposure/pubs/episuite.htm). Once downloaded, it could be used offline for educational and personal purposes. The interface allows selecting a number of options to use the suite as shown in Figure 2. It is possible to look for the chemical characteristics through the Chemical Abstracts Number (CAS) number, the simplified molecular-input line-entry system (SMILES) number (integrated chemical structure drawing tool) or chemical structure, and common chemical name. We can also use separate software tools and evaluate the chemical in every software tool separately, but, it is faster to complete the full analysis. It is particularly useful since results from some software tools are used for others.

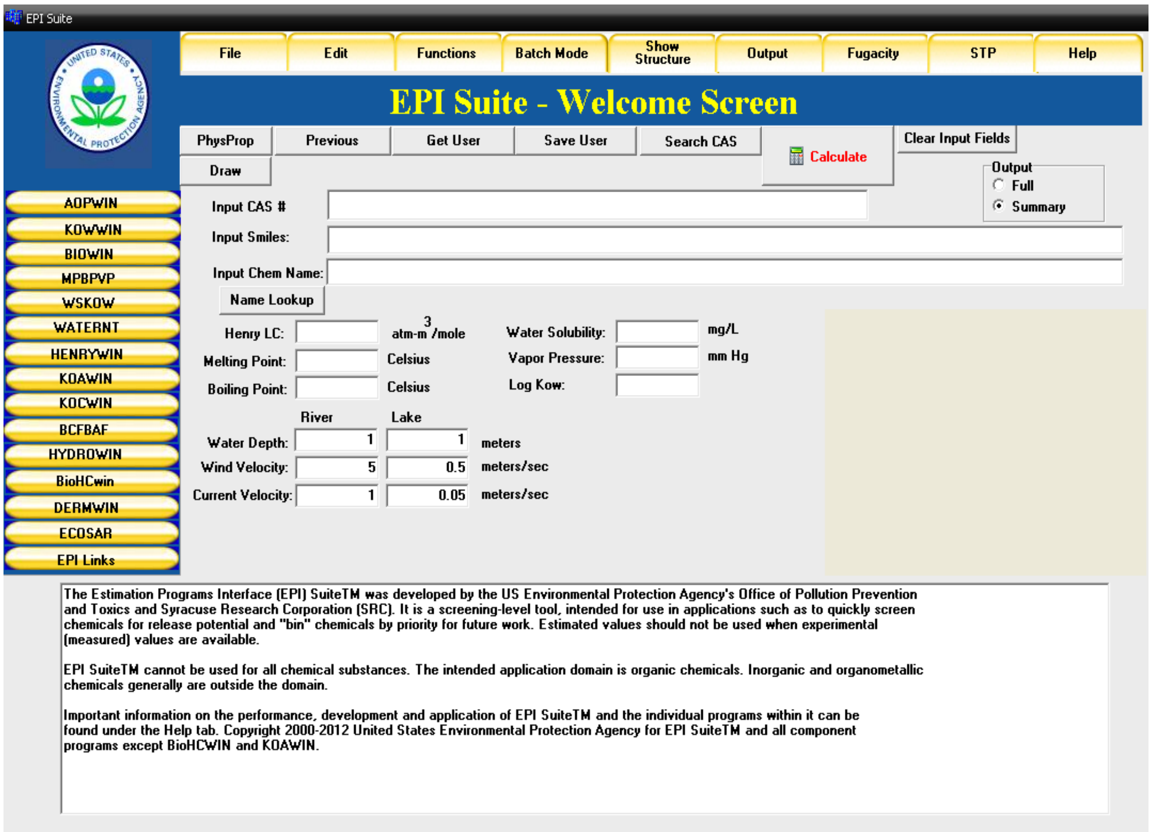


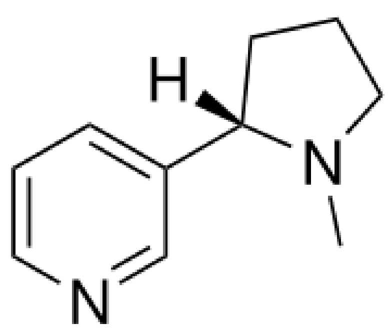
Figure 2. EPI Suite v4.11 main interface (http://www.epa.gov/oppt/exposure/pubs/episuite.htm)

In this learning module we represent two basic approaches to the chemical selection and their graphical representation via target plots. One case is somewhat simplified for well-known chemicals and the other two for chemicals that do not have experimental determined chemical and toxicological properties.

Case Study 1. Which chemical should have been used to kill Alexander the Great?

Ancient poison professionals had no need to use target plots to which poison to kill a king. It was quite obvious. However, which familiar modern poisonous chemical would they choose to kill Alexander the Great without harm to other people and the environment? We selected strychnine (to keep it historical) and a common substance that is available today, nicotine (Figure 3). They both were used as pesticides (1, 2) and both are poisonous enough to kill a human (10), (http://www.inchem.org/documents/pims/chemical/pim507.htm). The fatal dose of nicotine for an adult 70 kg human is 50-60 mg (single one time consumption) (http://www.cdc.gov/niosh/idlh/54115.html). Strychnine's lethal dosages vary in the range of 60 to 200 mg for an adult human (http://www.cdc.gov/niosh/idlh/57249.html).

Nicotine



Strychnine

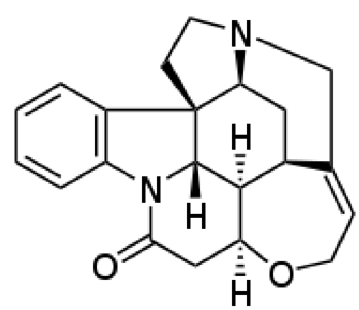


Figure 3. Structures of Nicotine and Strychnine (retrieved from Wikipedia http://en.wikipedia.org/wiki/Nicotine and http://en.wikipedia.org/wiki/Strychnine)

We used available online service "Scorecard" in order to get available data on selected chemicals for further comparison (http://scorecard.goodguide.com/chemical-profiles/).

It contains the information about 11,200 most widely used chemicals in the industries. The characteristics of chemicals in the database contain relative

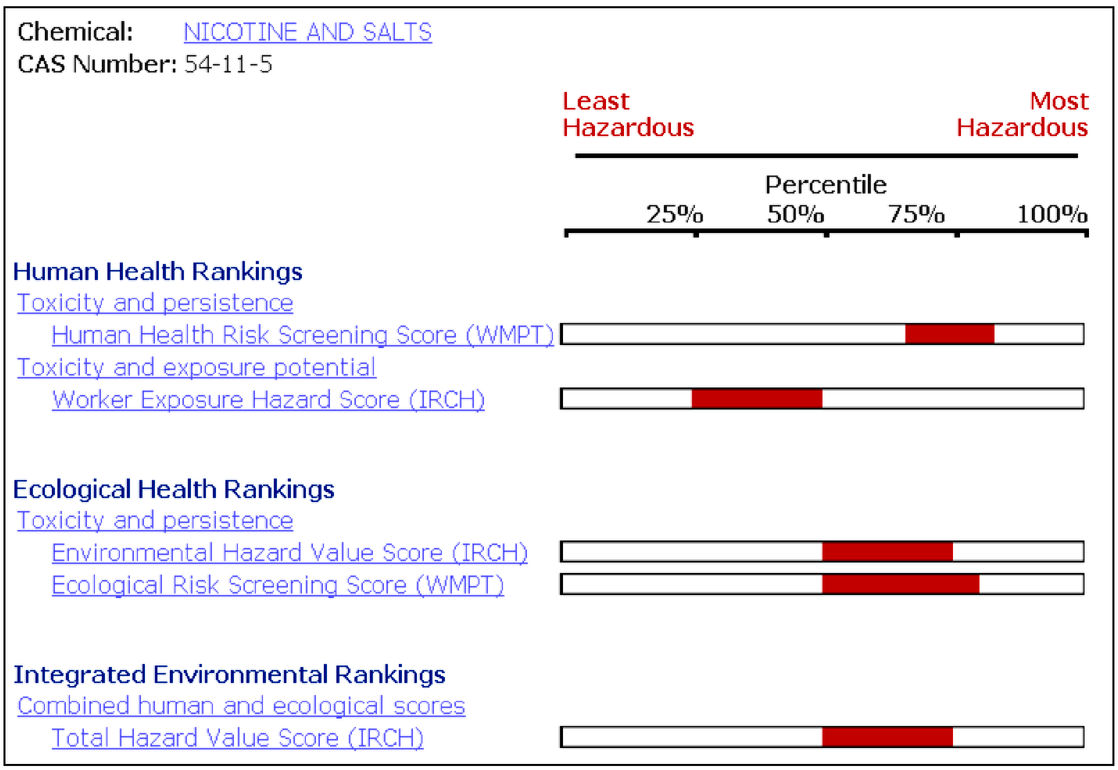


Figure 4. Hazard Ranking of Nicotine via "Scorecard"

information on "Hazard Rankings" of the chemical comparing to the other in 5 ranking systems (3-7). The rank of the chemicals is represented as percentile range (Figure 4, 5).

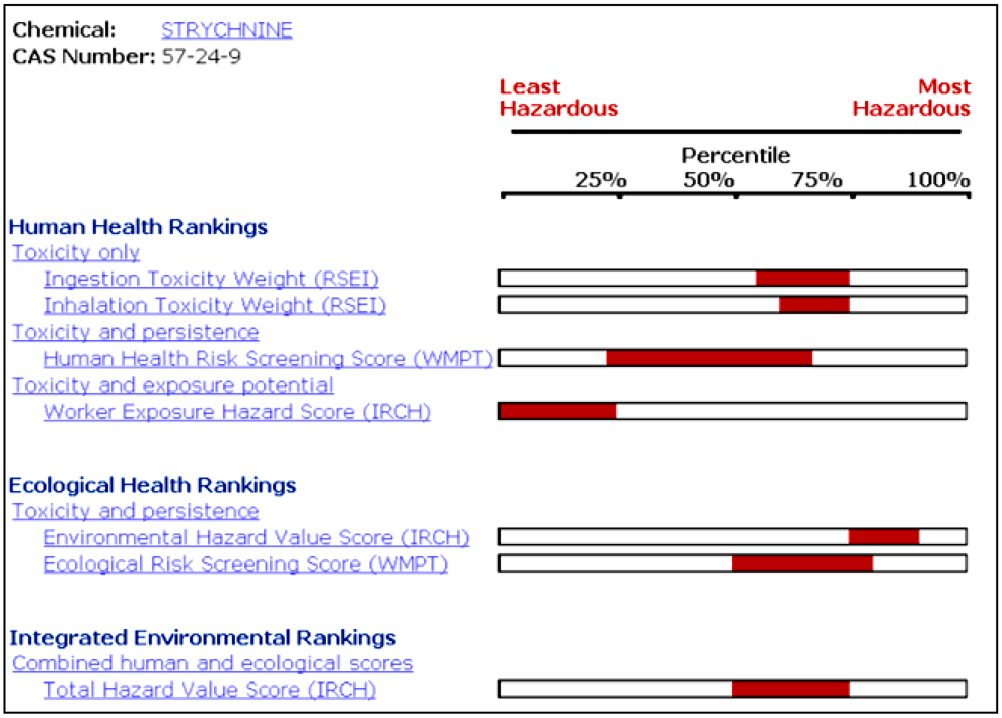


Figure 5. Hazard Ranking of Strychnine via “Scorecard”

The hazard characteristics of presented chemicals are different owing to variations of influence scales and categories. The “Integrated Environmental Ranking” scale shows the same percentile rank (50-75 %) for selected chemicals (Figure 4, 5). There is also an absence of data for the ingestion and inhalation toxicity for nicotine. For the target plot construction we assumed that the ingestion and inhalation toxicity of nicotine is in the same level as strychnine’s (Figure 6).

We used the Scorecard results, presented in percentile ranges, to built the partitioning scales with the lowest impact equal 0 (0 percent) and the highest impact 1 (100 %). With the plot ready we used mean values for each category and chemical to plot them out (Figure 6).

The target plot (Figure 6) indicates that nicotine is not as safe for poisoners ("workers") health as strychnine. Accidental exposures to nicotine therefore might fail the mission. At the same time Strychnine is more harmful for the environment (water, land, air and global influence).

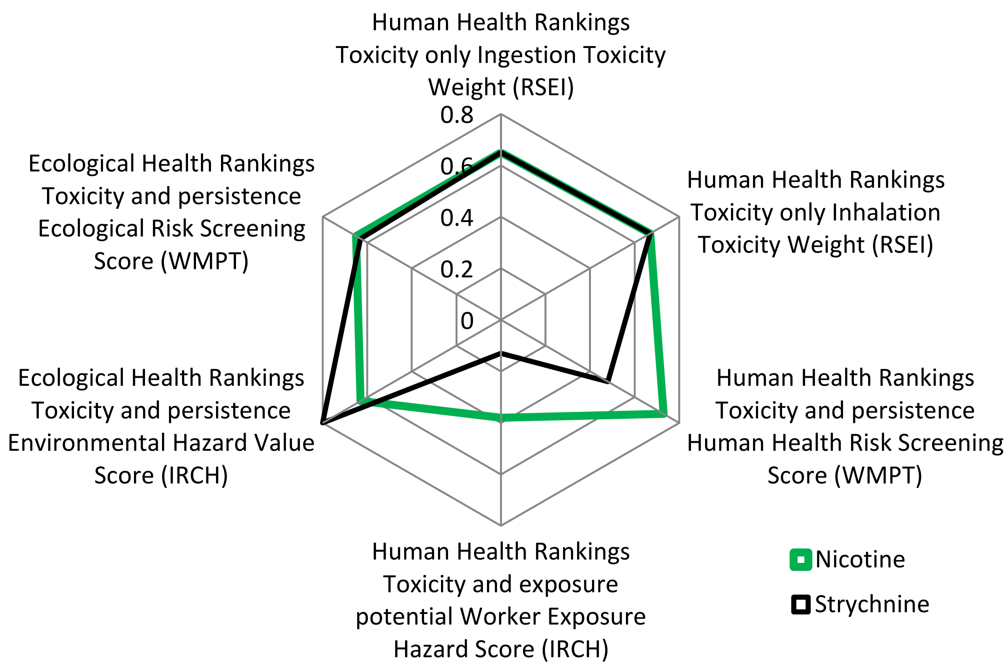


Figure 6. Target Plot Comparing Hazards of Nicotine and Strychnine Based on "Scorecard" Rankings

The same analysis performed via means of EPI Suite v4.11 gives more detailed results (Figure 7). The data received from EPI Suite software tools could be used for target plots construction. For this purpose, we recommend using Microsoft Office Excel or alternative table editor (e.g. Open Office). Comparing the results will require the researcher/student to select the appropriate categories that determine the environmental performance of the chemicals. As shown above, the results should categorized and given unified scale.

The target plot (Figure 7) shows that the chemicals have similar characteristics in most categories. Nicotine has a higher vapor pressure (easily evaporates in the air); it is more soil reactive and has lower environmental (water) migration potential than strychnine. It means that nicotine is likely to remain in soil or sludge, but if exposed to air will evaporate or remain in the air in aerosol particles.

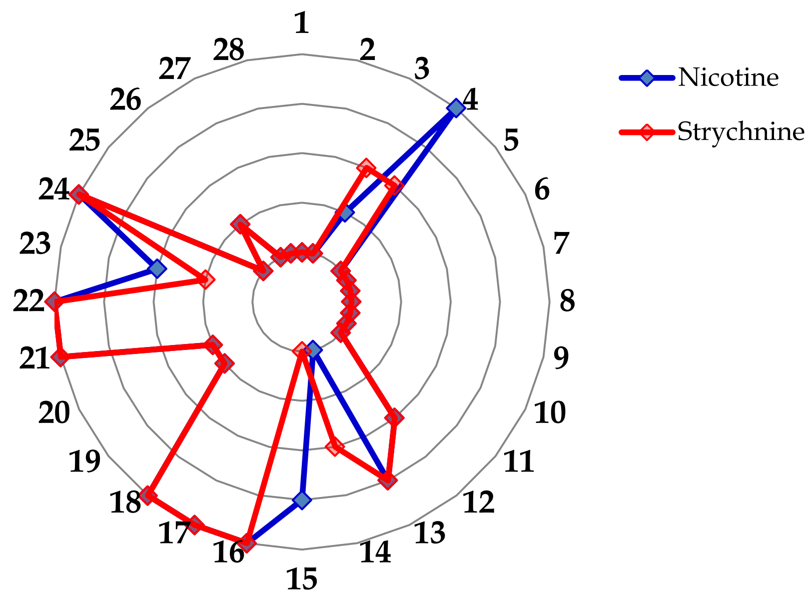


Figure 7. Target Plots for nicotine and strychnine Note: Categories are presented in **Appendix A:I**.

Strychnine, on the other hand, is somewhat more water soluble and has higher atmospheric oxidation potential (remains longer in the atmosphere). The target plot indicates that strychnine is more environmentally dangerous than nicotine.

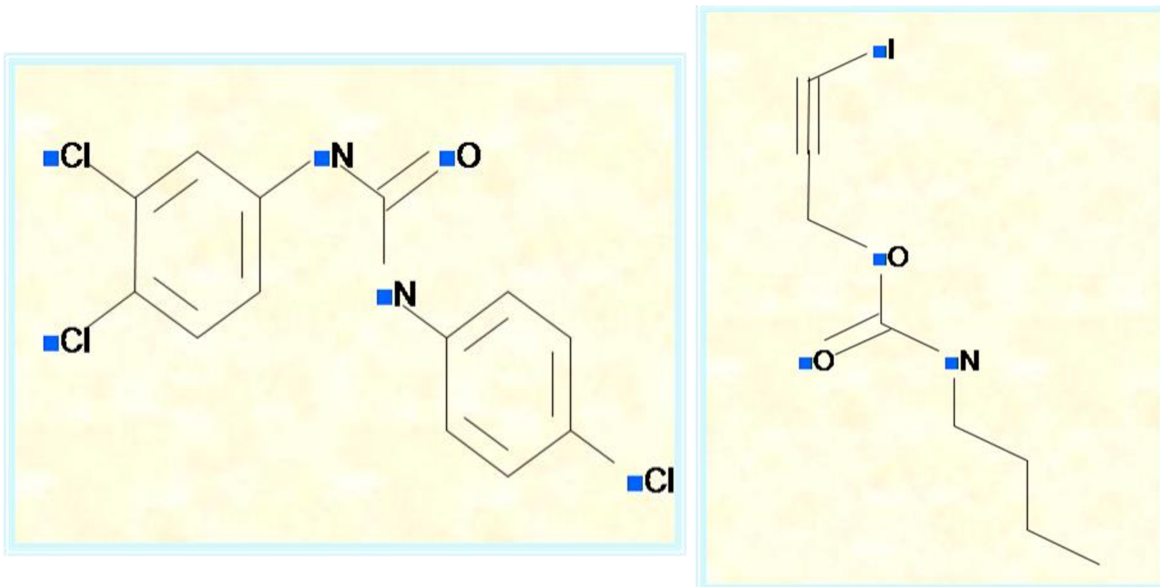
Suggested Assignment for Students

Some plastic bottles are known to contain potentially harmful chemicals (9). Compare Bisphenol A (CAS number 80-05-7) and Styrene (CAS number 100-42-5) using online service “Scorecard”. Present results on the target plots and discuss their characteristics. Compare results with experimental research results available online.

Case Study 2. Selecting between two fungicides in hand cream. Which one is more environmentally responsible?

Fungi can cause serious damages in agriculture, which result in yield quality and quantity loss, unless effective fungicide is used. Fungi can also ruin personal care products like hand creams. TSCA was passed to prevent harmful chemical from entering the market. We will determine which fungicide is more environmentally responsible using a target plot.

For this case, we will evaluate which fungicide should we add to our hand cream to prevent it from being spoiled by fungal growth. For this case, we are a formulator and our choices will drive the market to produce the better fungicide because formulators will buy only the best one. We consider two commercially available fungicides: UBC (Urea Based Compound) and CBC (Carbamate Based Compound). Because we care not only about effectiveness of the fungicide; but, also about its ultimate environmental and health consequences, we will estimate the main environmental qualities. The chemical structure is given in Figure 8.



Urea Based Compound   Carbamate Based Compound

Figure 8. Chemical Structures of UBC and CBC fungicides

As mentioned above we use a software tool SMILES (Simplified Molecular Input Line Entry System) to draw the structures and "upload" chemicals this way to the program (Figure 9). The 2D drawing is reflected in the SMILES, which present the structure in a form of a line notation, which the EPI Suite v4.11 utilizes for calculations.

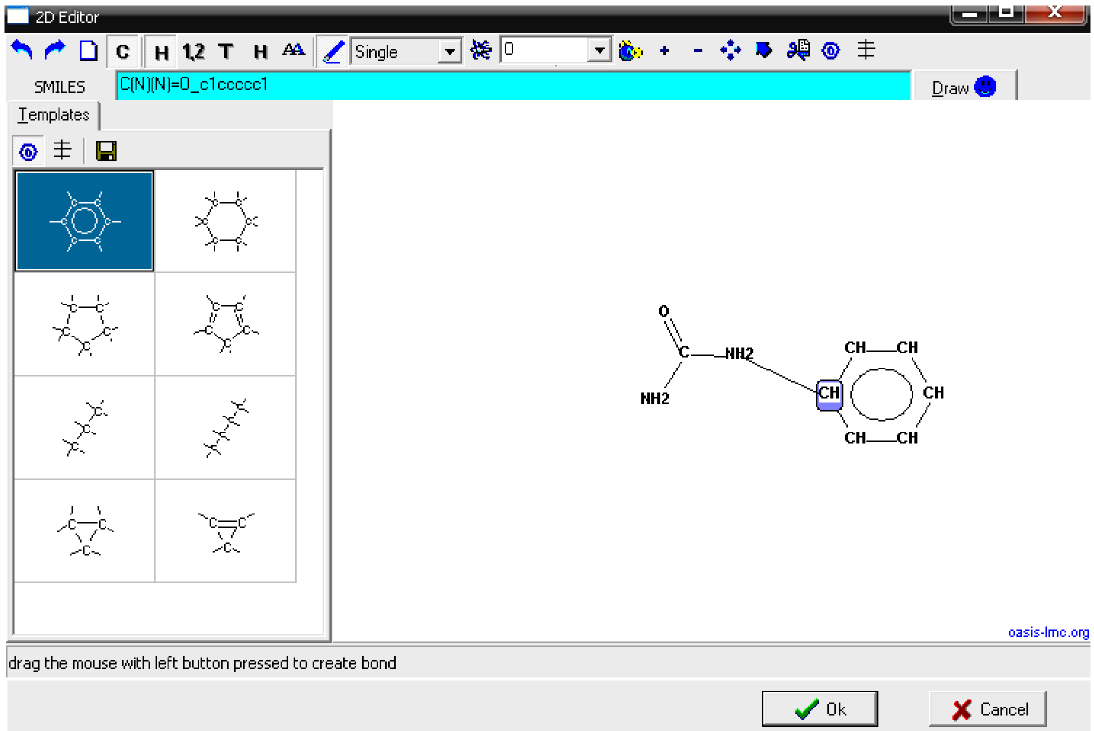


Figure 9. 2D editor screen of EPI Suite v4.11 used for drawing and getting SMILES code

We developed a target plot that plots 16 chemical properties which can be used to assess the chemicals environment performance. We have chosen the scales that are shown in Figure 10 according to highest to lowest observed values. We have also arranged the target plot such that chemical had better performance in one category if it was closer to the inner part of the target plot or "bulls eye". In some cases, such as solubility, a scale starts with the highest solubility near the "bulls eye". This is because a chemical with high solubility would disperse more readily and would not bioaccumulate as much as one that has a low solubility. This subjective determination is open to other strategies based on the users' need but will use the one we developed and is shown Figure

10. We have arranged Figure 10 into 4 main categories: physico-chemical properties, environmental fate, and occupational influence and disposal properties of chemicals. As can be seen, every chemical properties has its own scale, and we have stated the lowest impact points are plotted near the “bulls eye” and the high-impact levels are placed on the outer edges of the plot.

We used the software package of EPI Suite v4.11 to estimate the values for every category and plotted them as shown in Figure 11.

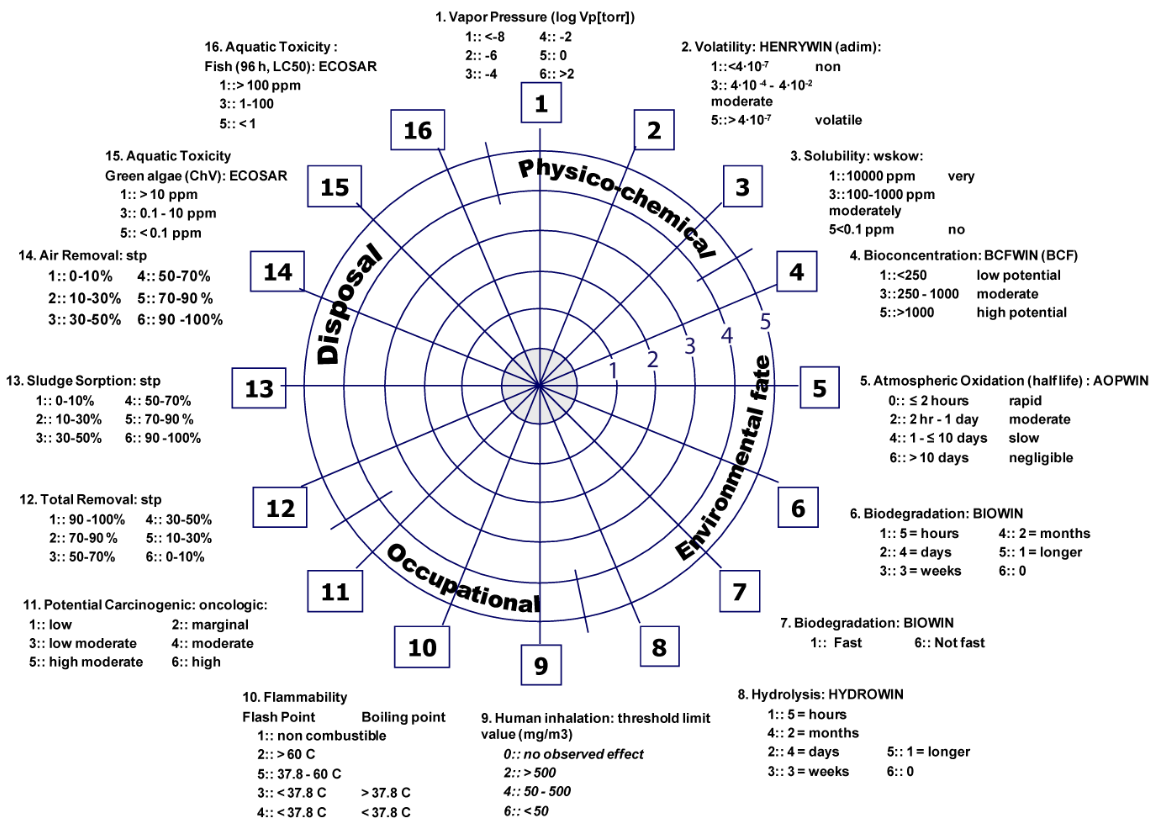
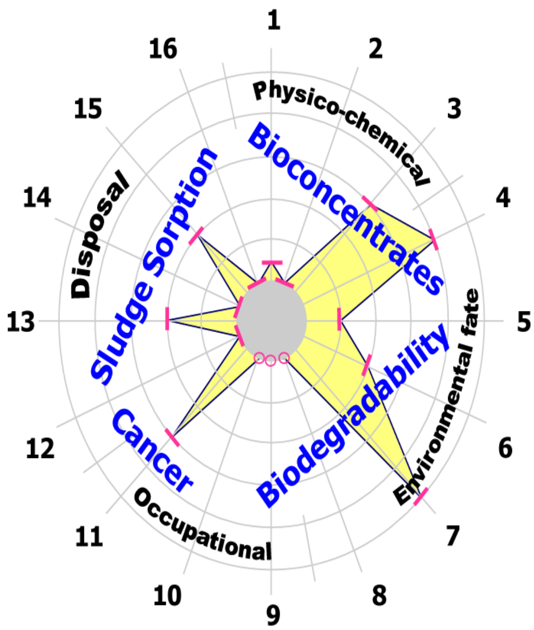
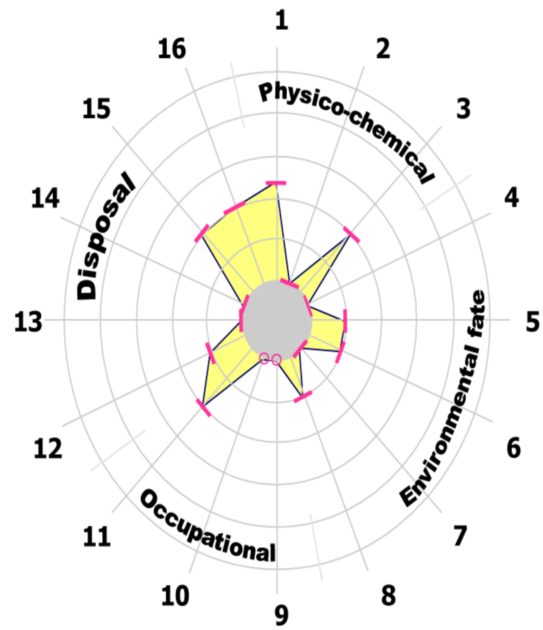


Figure 10. Target plot for fungicides comparison



Urea Based Compound



Carbamate Based Compound

Figure 11. Target Plots for UBC and CBC Fungicides
Note: Categories are presented in Figure 10. The excel file is added.

The UBC fungicide presents a higher environmental risk due to its higher carcinogenic and bioconcentration potential, low biodegradability and high sorption to sewage sludge (Figure 12). The CBC fungicide shows high levels of aquatic toxicity, lower cancer risk, and higher degradability in the environment. Consequently, a typical waste water treatment plant that contains this fungicide may need advance treatment.

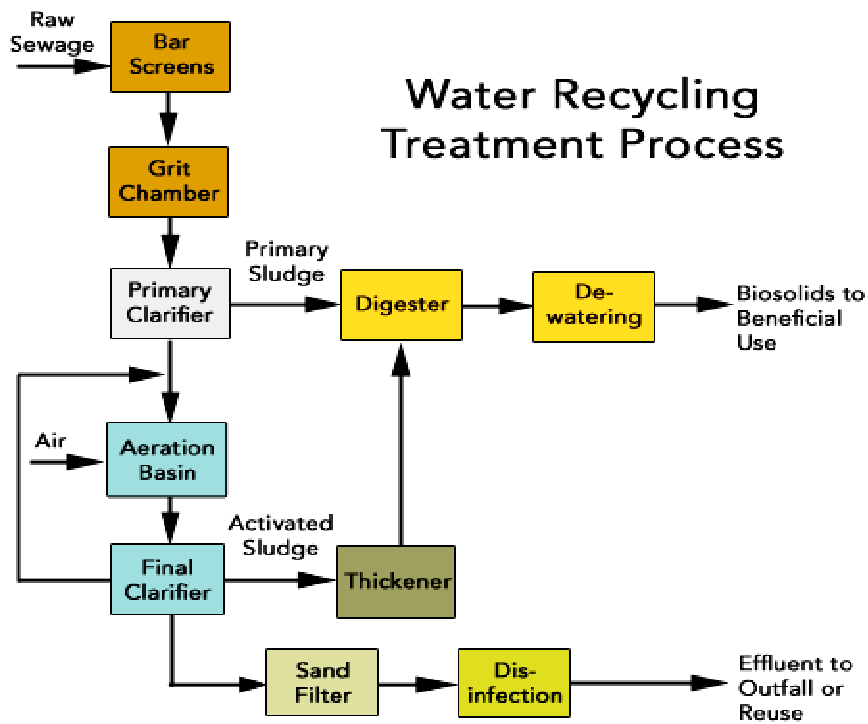


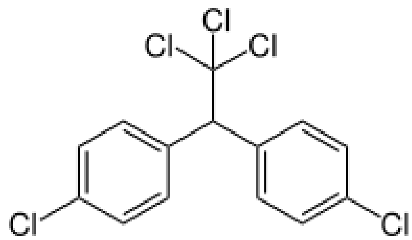
Figure 12. Water recycling treatment process at typical wastewater treatment plant (http://www.saws.org/your_water/recycling/Centers/treatment.cfm)

Case Study 3. How to get rid of mosquitoes with less environmental impacts?

Fifty years ago, Rachel Carson's "Silent Spring" set off the alarm about the dangers of DDT usage. DDT caused the thinning of egg shell of predictor birds and this resulted in total reproductive failure. After the Stockholm Convention, the US banned the use of DDT (dichlorodiphenyltrichloroethane) for agricultural purposes in the USA. However, the production of DDT remains at 3,000-4,000 tons annually, and is used to control malaria vectors (indoor residual spraying) [8]. On the other hand, one of the widely used mosquito repellents is the DEET (*N*,*N*-Diethyl-*meta*-toluamide)(11).The chemical structures are given in Figure 12.

If you search the available data bases, we cannot find a complete list of the chemical properties. In this case, we may use EPI Suite, which has been developed by EPA's OPPT and Syracuse Research Corporation.

DDT



DEET

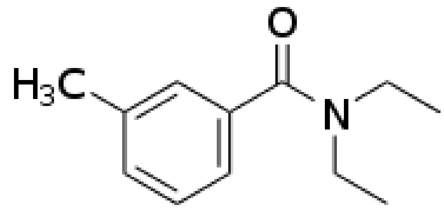


Figure 12. Structures of DDT and DEET (retrieved from Wikipedia http://en.wikipedia.org/wiki/DDT and http://en.wikipedia.org/wiki/DEET)

For the comparative evaluation of DDT and DEET we used default values of water depth, wind velocity and water velocity. After the selection of the chemical the full report is generated in a separate window ("Results Window" button), where one can review all results or flagged results of every software tool. Results could be saved in text formats and printed. Short results are also available on the lower part of the main screen as flagged tabs.

We used a 5 point scale to construct a target plot (1 – the lowest impact in the center of a target plot and 5 – the highest). This way we were able to plot the results in a single scale target plot (Figure 13).

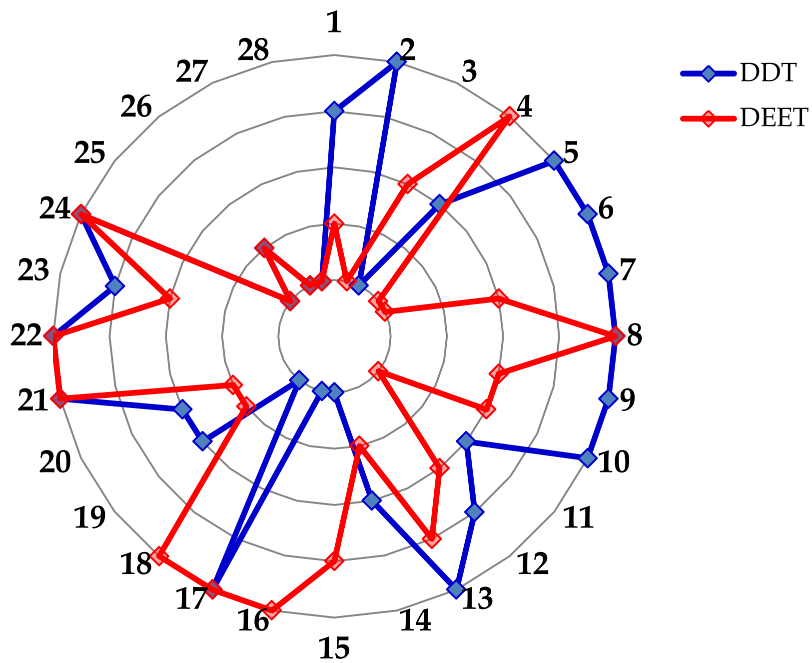


Figure 13. Target Plots for DDT and DEET

Note: Categories are presented in **Appendix A:I**.

Suggested Assignment for Students

Malathion (CAS number 121-75-5) and Bromomethane (CAS number 74-83-9) are well known insecticides. Compare them using P2 Framework (EPI Suite v4.11). Present results on the target plots and discuss their characteristics. Which insecticide is more dangerous for human health? What parts of environment will be affected via their release?

Suggested References for Students to Review

http://www.epa.gov/opptintr/sf/pubs/p2frame-june05a2.pdf

http://www.epa.gov/oppt/exposure/pubs/episuite.htm

Appendix A:I.

Table 1. Selected Categories for Chemicals Comparison

#	Category	Minimum, = 1 Pt	Maximum, = 5 Pt
1	Bioconcentration potential, Log KOW	<2	>8
2	Bioconcentration factor, Log BCF	<3	>3,7
3	Water solubility, ppm	<0.1	>10,000
4	Vapor pressure, mm Hg	$<10^{-8}$	$>10^{-4}$
	Aquatic toxicity, ppm		
5	- Fish, LC50, 96h	>10	≤1
6	- Daphnid, LC50, 48h	>10	≤1
7	- Green Algae, EC50, 96h	>10	≤1
8	- Fish, ChV	>10	≤0.1
9	- Daphnid, ChV	>10	≤0.1
10	- Green Algae, ChV	>10	≤0.1
11	Volatility, atm-m^3/mole	$<10^{-7}$	$>10^{-3}$
12	Biodegradation primary, half-life	Hours	Recalcitrant (years)
13	Biodegradation ultimate, half-life	Hours	Recalcitrant(years)
14	Atmospheric oxidation, half-life	<2 hours	>1 month
15	Environmental migration potential, Log Koc	>4.5	<1.2
	Predicted Fate in a Wastewater Treatment Facility, %		
16	- Total removal	>80	0-20
17	- Total biodegradation	>80	0-20
18	- Total sludge sdsorption	>80	0-20
19	Environmental reaction, total, %	>80	0-20
20	Environmental advection, total, %	0-20	>80
21	Air reaction, %	>80	0-20

#	Category	Minimum, = 1 Pt	Maximum, = 5 Pt
22	Water reaction, %	>80	0-20
23	Soil reaction, %	>80	0-20
24	Sediment reaction, %	>80	0-20
25	Air advection, %	0-20	>80
26	Water advection, %	0-20	>80
27	Soil advection, %	0-20	>80
28	Sediment advection, %	0-20	>80

APPENDIX B

Environmental emissions incurred from additional material and energy investment (cost) or saved from avoided damage (benefit) for different mitigation scenarios. All the values are in tons (1000 kg).

		GW	A	HH	E(A)	E(W)	OD	SF	ET	HH-C	HH-NC
Cost	S1	71700	244	69.8	6.11	0.00657	0.0079	3130	4.215	13.97	41455
	S2	130000	444	127	11.1	0.0119	0.0144	5680	7.665	25.345	75330
	S3	277000	946	270	23.6	0.0254	0.0306	12100	16.35	54.05	160550
	S4	519000	1770	505	44.2	0.0475	0.0572	22600	30.5	101	299750
	S5	1320000	4490	1280	112	0.121	0.145	57500	77.5	256.45	763600
	S6	1630000	5570	1590	139	0.15	0.18	71300	96.15	318	945500
Benefit	S1	918000	3130	893	78.2	0.0841	0.101	40000	54	178.95	529950
	S2	1530000	5210	1490	130	0.14	0.169	66700	90	298	883200
	S3	2160000	7370	2100	184	0.198	0.238	94300	127.5	421	1251950
	S4	2860000	9750	2780	243	0.262	0.315	125000	168.5	557	1652000
	S5	4100000	14000	3990	349	0.376	0.452	179000	241	798.5	2374000
	S6	4830000	16500	4700	411	0.442	0.532	211000	284	943	2795000

Legend:

GW: Global Warming (t CO_2 Eqv.)

A: Acidification (Air) (t SO_2 Eqv.)

HH: Human Health Criteria (Air) (t PM_{10} Eqv.)

E(A): Eutrophication (Air) (t N Eqv.)

E(W): Eutrophication (Water) (t N Eqv.)

OD: Ozone Depletion (t CFC-11 Eqv.)

SF: Smog Formation (Air) (t O_3 Eqv.)

ET: Ecotoxicity (Mid Estimate) (t 2,4 D Eqv.)

HH-C: Human Health - Cancer (Mid Estimate) (t Benzene Eqv.)

HH-NC: Human Health - Non-Cancer (Mid Estimate) (t Toluene Eqv.)

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